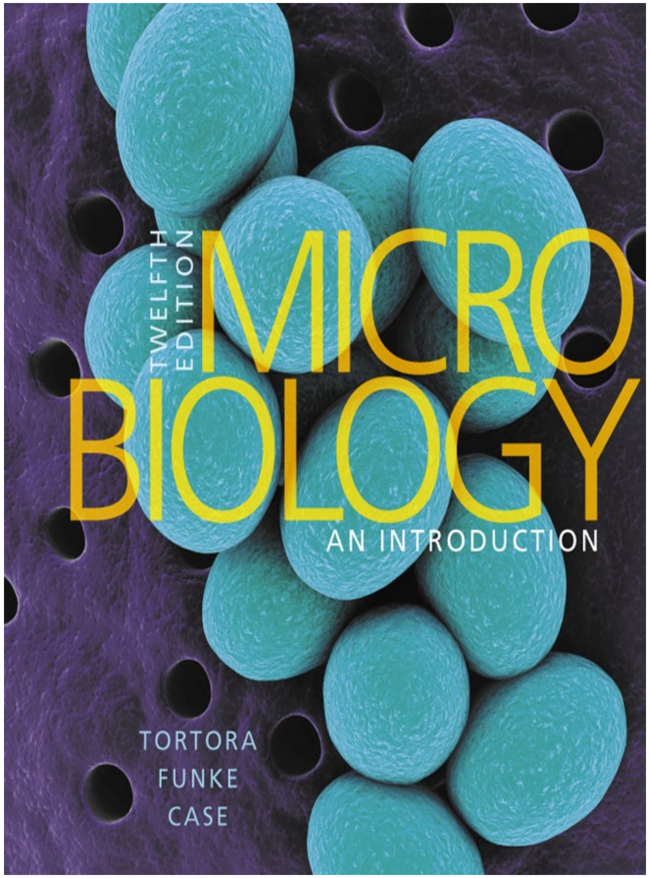
Microbiology an Introduction

Twelfth Edition



Chapter 5

Microbial Metabolism

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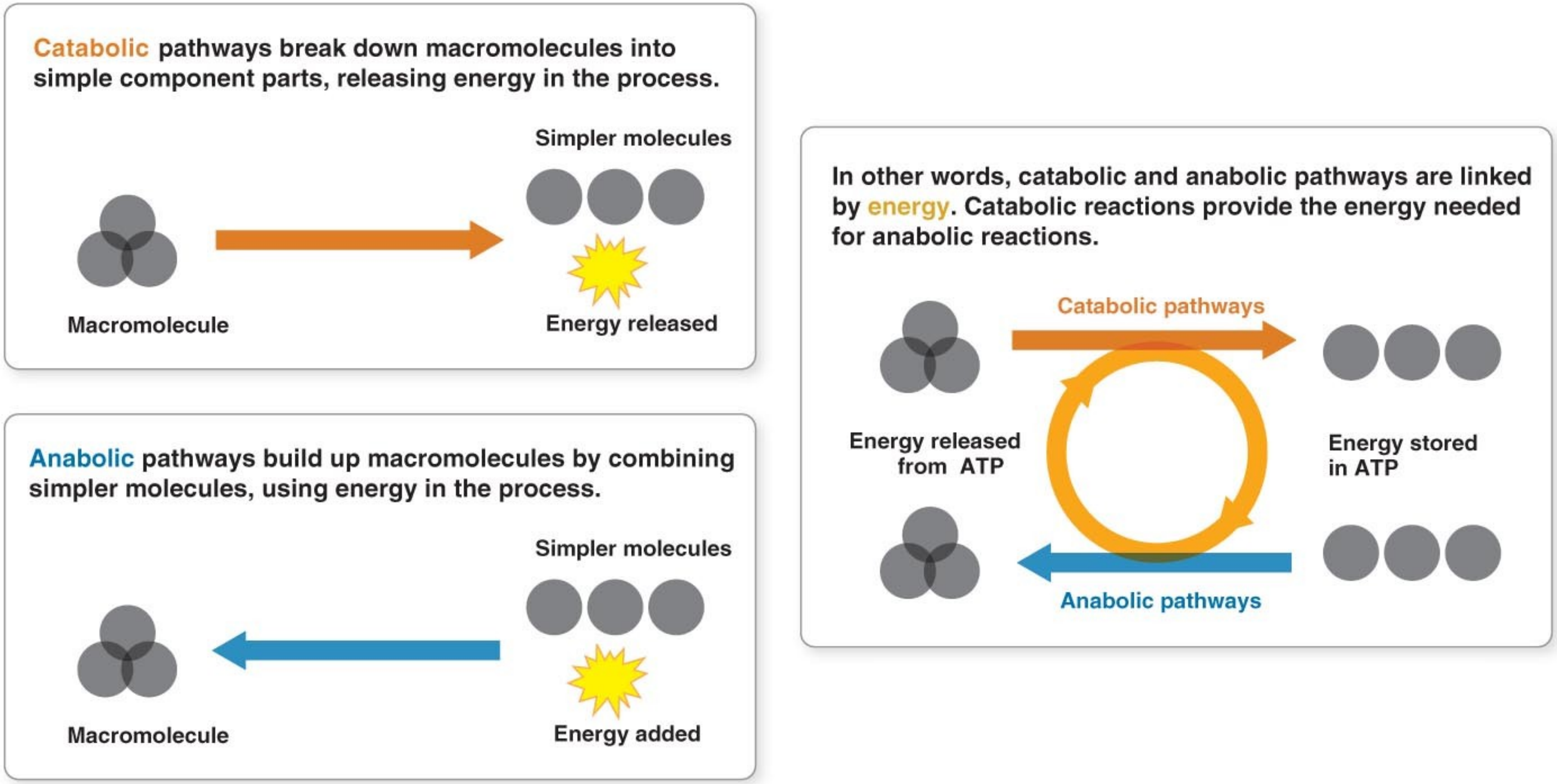
Dental Plaque Consists of Bacteria

Big Picture: Metabolism (1 of 2)

- Metabolism is the buildup and breakdown of nutrients within a cell
- These chemical reactions provide energy and create substances that sustain life

Big Picture pg. 108



Big Picture: Metabolism (2 of 2)

- Although microbial metabolism can cause disease and food spoilage, many pathways are beneficial rather than pathogenic

Big Picture pg. 109

Drugs: The pharmaceutical industry uses a variety of bacteria and fungi in the production of antibiotics, such as penicillin, (derived from the *Penicillium* fungus, shown on the right). Bacitracin, erythromycin, and other treatments such as vaccines, vitamins, and enzymes are also derived from microbial metabolism.

KEY CONCEPTS

- Enzymes facilitate metabolic reactions.
- ATP is used by microbes and other cells to manage energy needs.
- Catabolic reactions couple with ATP synthesis.
- Anabolic reactions couple with ATP breakdown.

Catabolic and Anabolic Reactions (1 of 3)

Learning Objectives

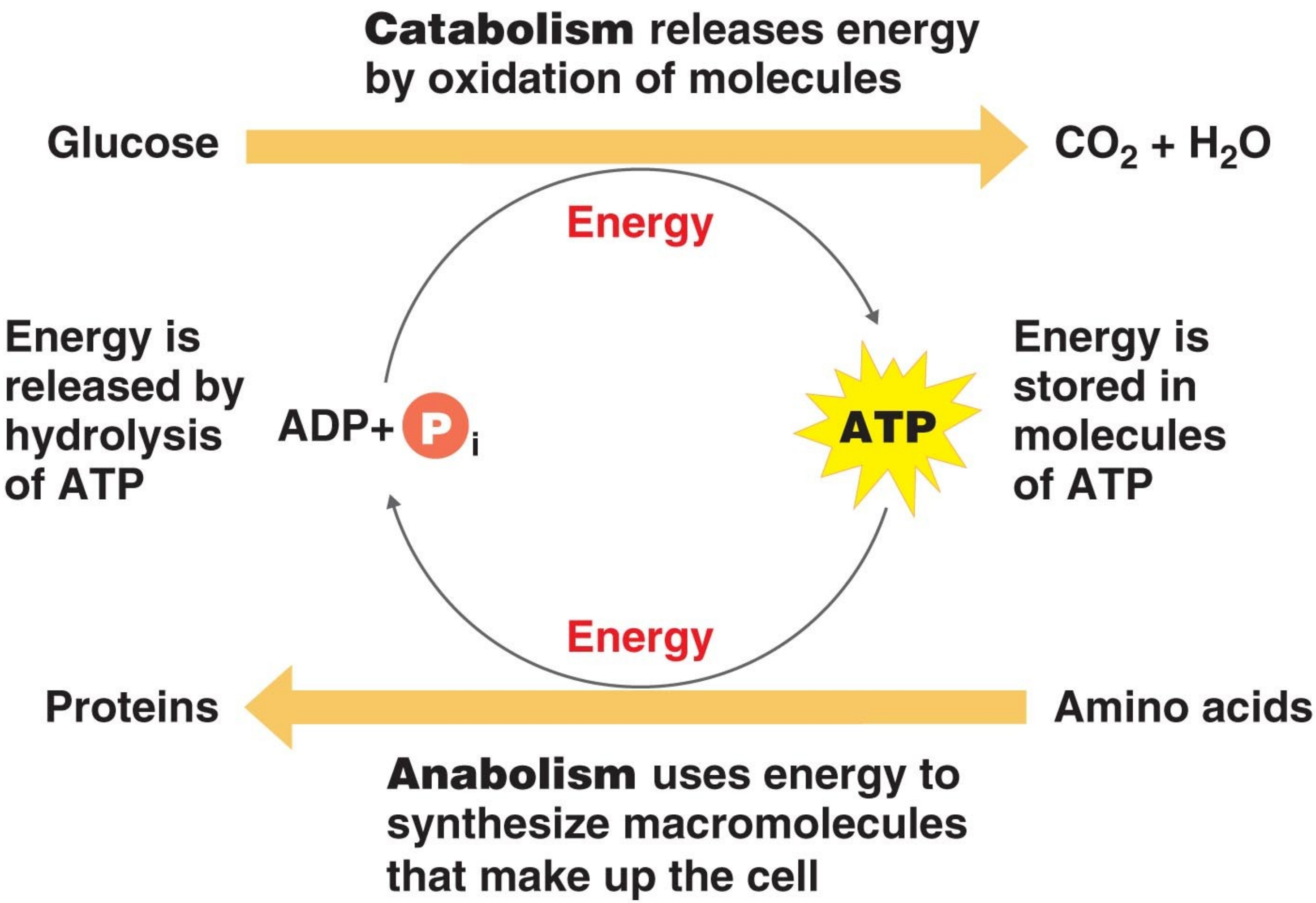
5-1 Define **metabolism**, and describe the fundamental differences between anabolism and catabolism.

5-2 Identify the role of ATP as an intermediate between catabolism and anabolism.

Catabolic and Anabolic Reactions (2 of 3)

- **Catabolism:** breaks down complex molecules; provides energy and building blocks for anabolism; exergonic
- **Anabolism:** uses energy and building blocks to build complex molecules; endergonic

Figure 5.1 The role of ATP in Coupling Anabolic and Catabolic Reactions



Catabolic and Anabolic Reactions (3 of 3)

- **Metabolic pathways** are sequences of enzymatically catalyzed chemical reactions in a cell
- Metabolic pathways are determined by enzymes
- Enzymes are encoded by genes

Metabolism: Overview

PLAY **Animation: Metabolism: Overview**

Check Your Understanding-1

Check Your Understanding

- ✓ Distinguish catabolism from anabolism.
  5-1
- ✓ How is ATP an intermediate between catabolism and anabolism?
  5-2

Enzyme

Learning Objectives

5-3 Identify the components of an enzyme.

5-4 Describe the mechanism of enzymatic action.

5-5 List the factors that influence enzymatic activity.

5-6 Distinguish competitive and noncompetitive inhibition.

5-7 Define **ribozyme**.

Collision Theory

- The **collision theory** states that chemical reactions occur when atoms, ions, and molecules collide
- **Activation energy** is the collision energy required for a chemical reaction to occur
- **Reaction rate** is the frequency of collisions containing enough energy to bring about a reaction
  - Reaction rate can be increased by enzymes or by increasing temperature, pressure, or concentration

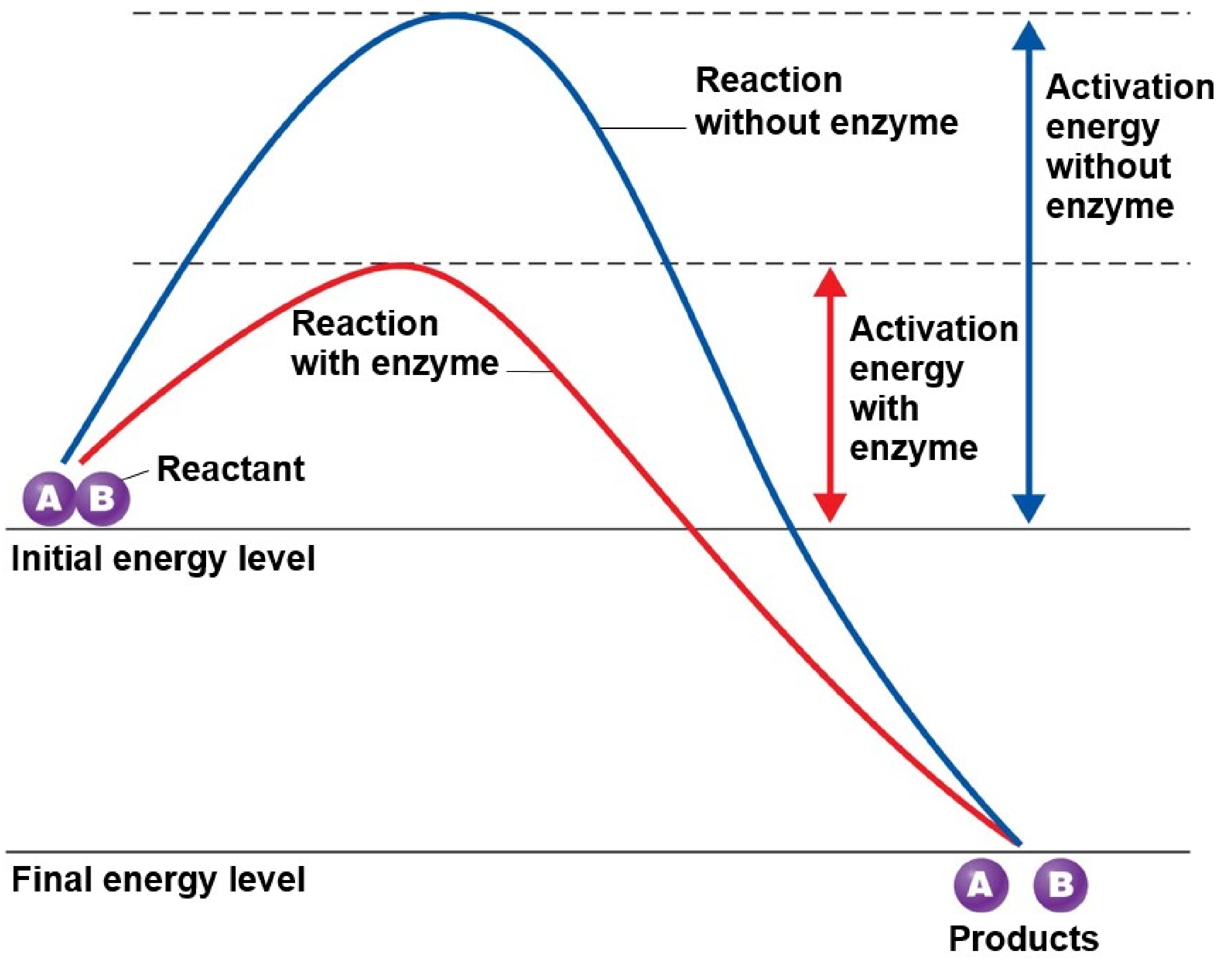
Enzymes and Chemical Reactions (1 of 2)

- **Catalysts** speed up chemical reactions without being altered
- **Enzymes** are biological catalysts
- Enzymes act on a specific **substrate** and lower the activation energy

Enzymes: Overview

PLAY **Animation: Enzymes: Overview**

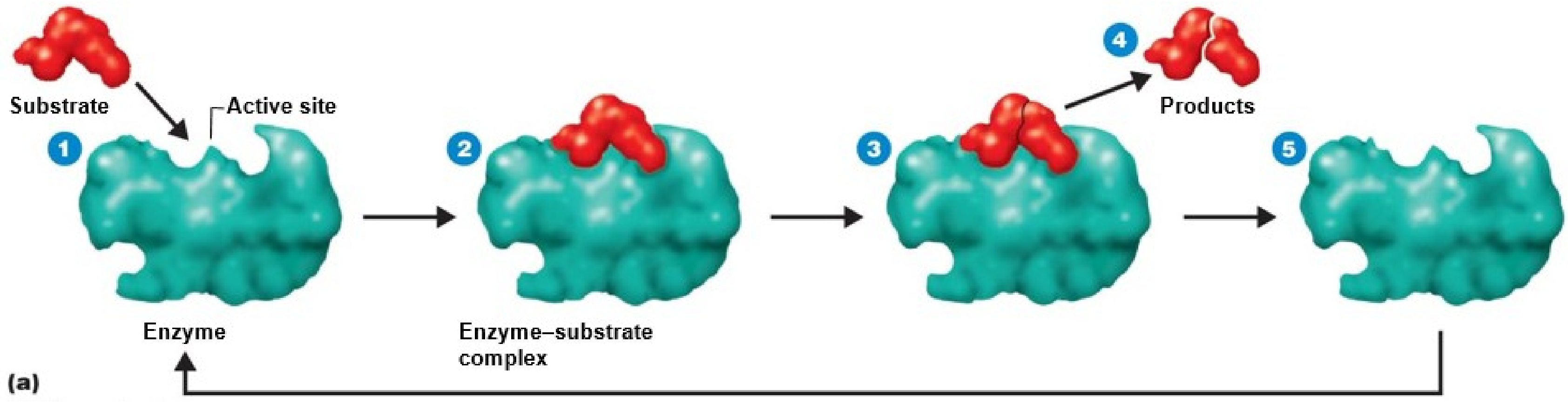
Figure 5.2 Energy Requirements of a Chemical Reaction



Enzymes and Chemical Reactions (2 of 2)

- Substrate contacts the enzyme's active site to form an **enzyme-substrate complex**
- Substrate is transformed and rearranged into **products,** which are released from the enzyme
- Enzyme is unchanged and can react with other substrates

Figure 5.3a The Mechanism of Enzymatic Action



Enzymes: Steps in a Reaction

PLAY **Animation: Enzymes: Steps in a Reaction**

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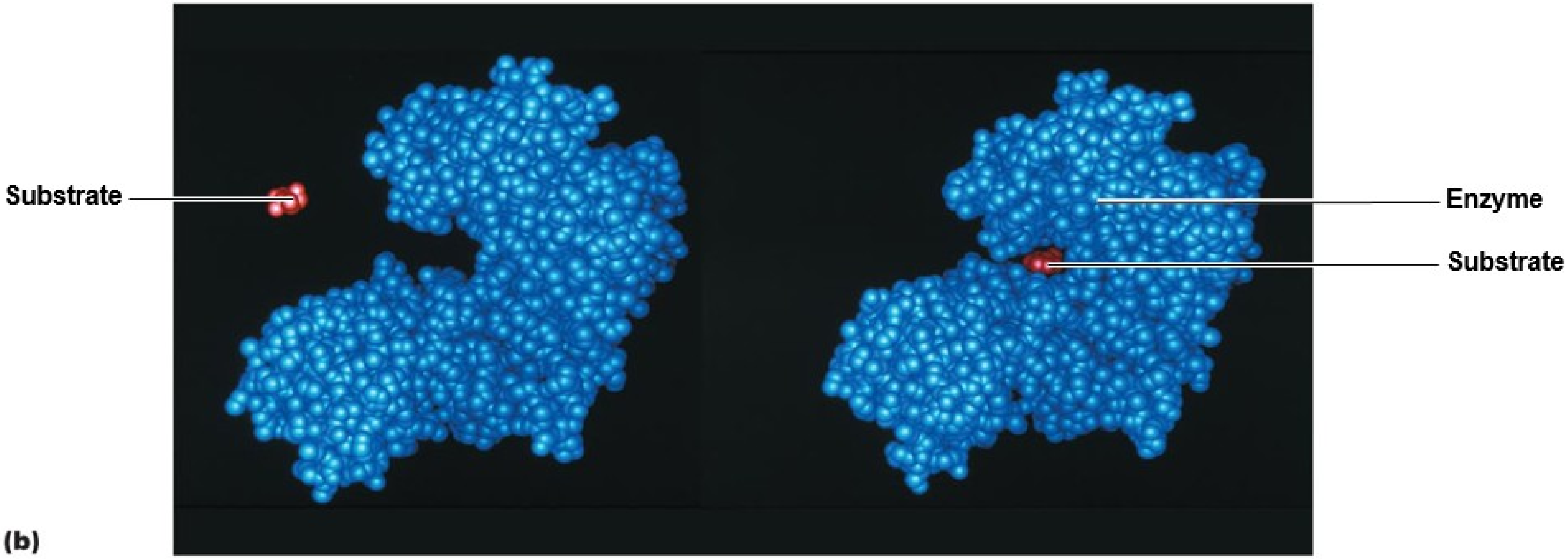
Figure 5.3b The Mechanism of Enzymatic Action



Enzyme Specificity and Efficiency

- Enzymes have specificity for particular substrates
- **Turnover number** is the number of substrate molecules an enzyme converts to a product per second
  - Generally 1 to 10,000

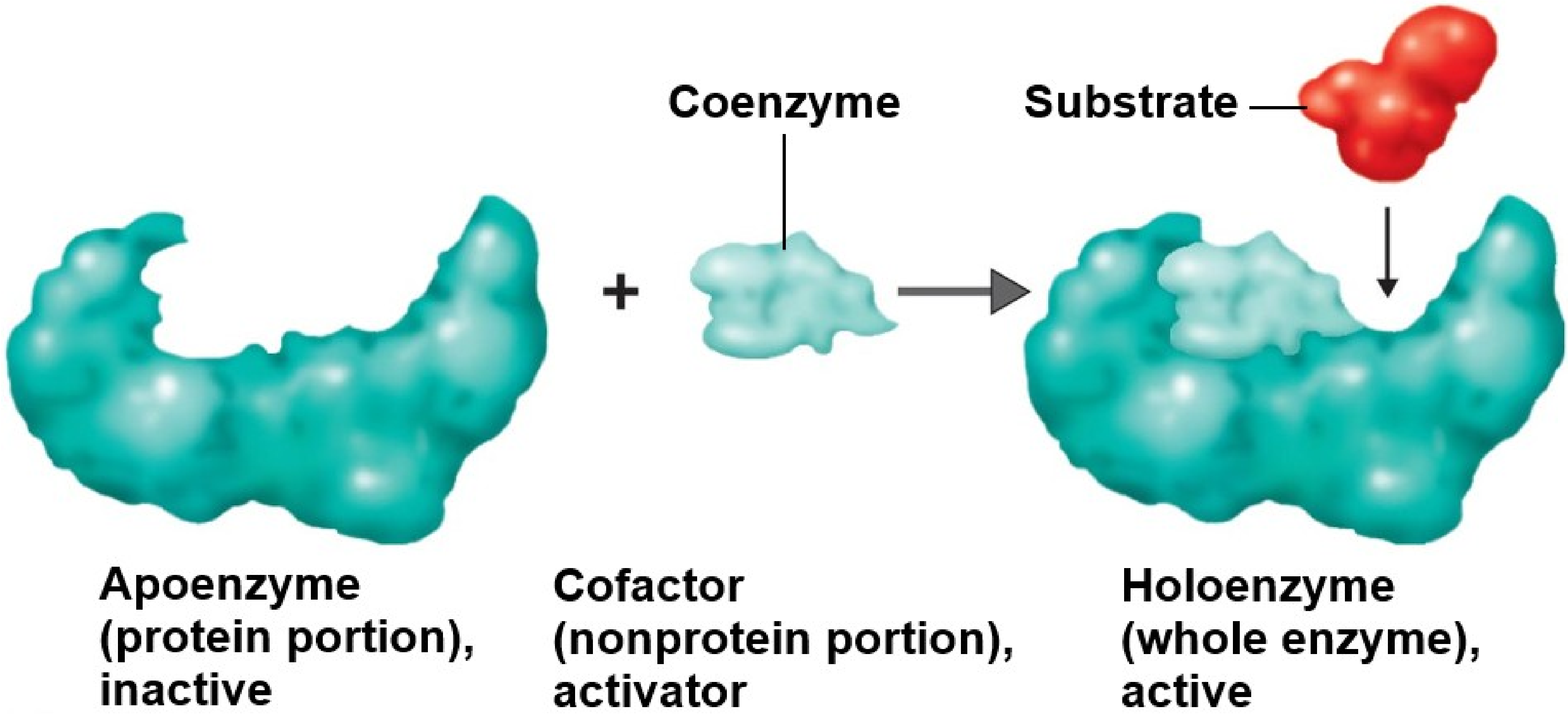
Naming Enzymes

- Names of enzymes usually end in *ase;* grouped based on the reaction they catalyze
- **Oxidoreductase:** oxidation-reduction reactions
- **Transferase:** transfer functional groups
- **Hydrolase:** hydrolysis
- **Lyase:** removal of atoms without hydrolysis
- **Isomerase:** rearrangement of atoms
- **Ligase:** joining of molecules; uses ATP

Enzyme Components (1 of 2)

- **Apoenzyme:** protein portion
- **Cofactor:** nonprotein component
  - **Coenzyme:** organic cofactor
- **Holoenzyme:** apoenzyme plus cofactor

Figure 5.4 Components of a Holoenzyme



Enzyme Components (2 of 2)

- Assist enzymes; electron carriers
  - **Nicotinamide adenine dinucleotide (NAD^+)**
  - **Nicotinamide adenine dinucleotide phosphate (NADP+)**
  - **Flavin adenine dinucleotide (FAD)**
  - **Coenzyme A**

Factors Influencing Enzyme Activity (1 of 2)

- Temperature
- pH
- Substrate concentration
- Inhibitors

Factors Influencing Enzyme Activity (2 of 2)

- High temperature and extreme pH denature proteins
- If the concentration of substrate is high (**saturation**), the enzyme catalyzes at its maximum rate

Figure 5.6 Denaturation of a Protein

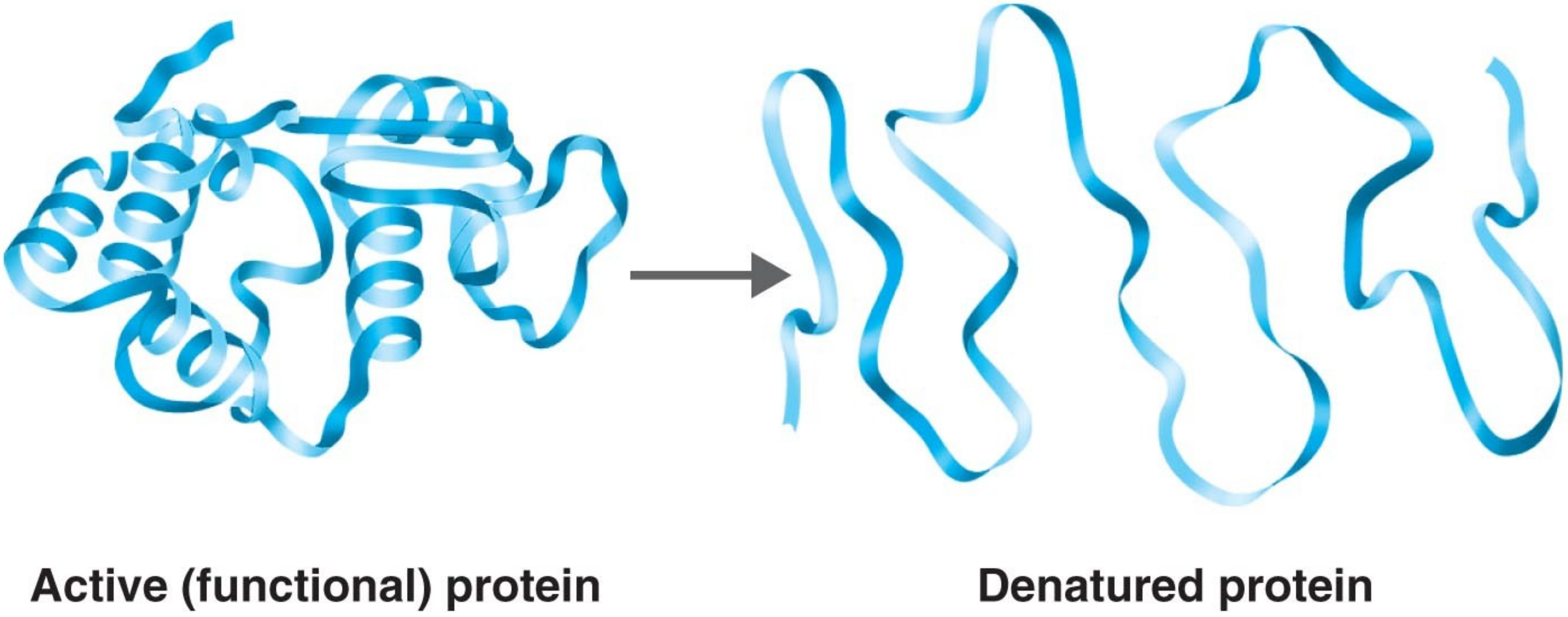


Figure 5.5a Factors that Influence Enzymatic Activity, Plotted for a Hypothetical Enzyme

(a) Temperature.
The enzymatic activity (rate of reaction catalyzed by the enzyme) increases with increasing temperature until the enzyme, a protein, is denatured by heat and inactivated. At this point, the reaction rate falls steeply.

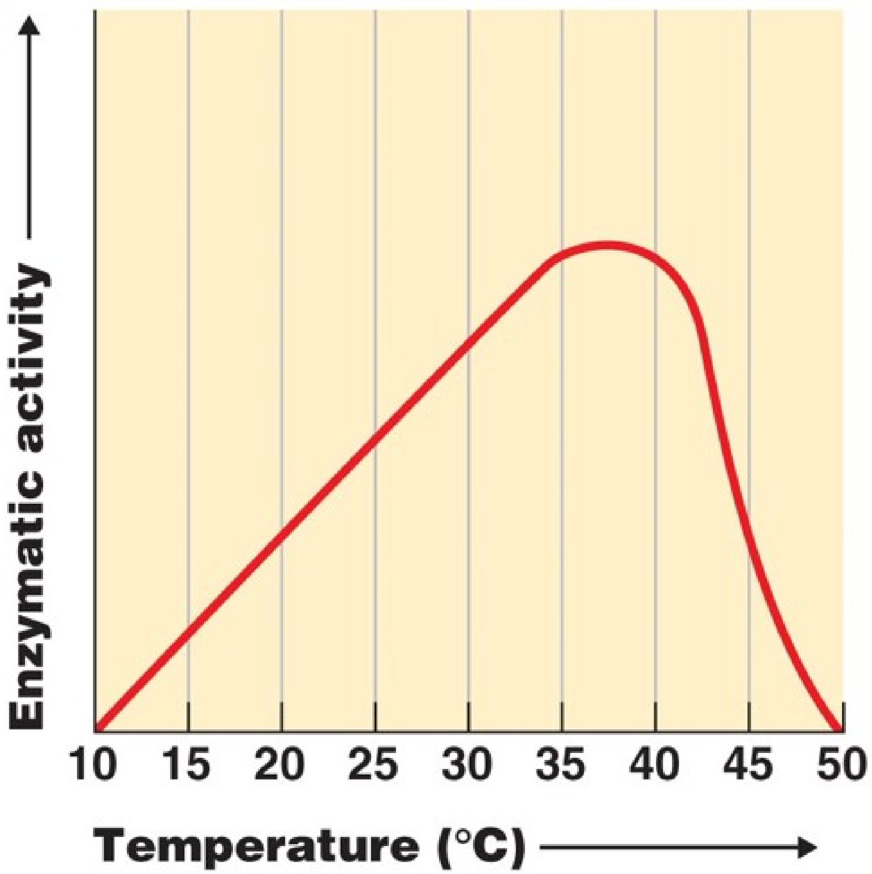


Figure 5.5b Factors that Influence Enzymatic Activity, Plotted for a Hypothetical Enzyme

(b) pH. The enzyme illustrated is most active at about pH 5.0.

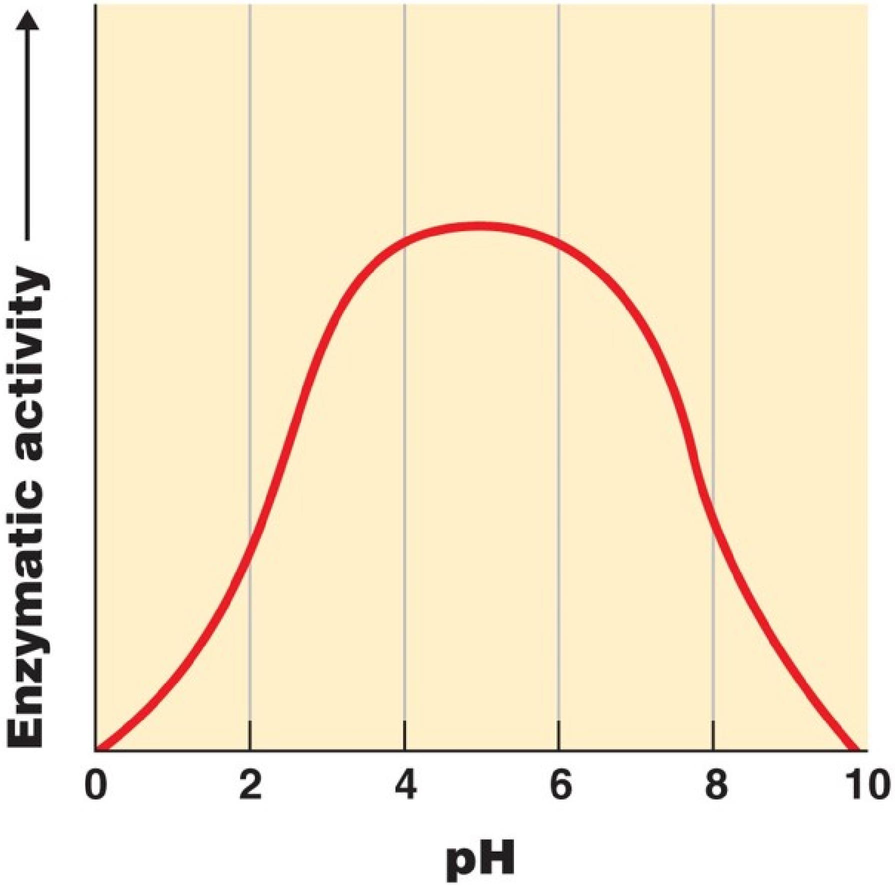
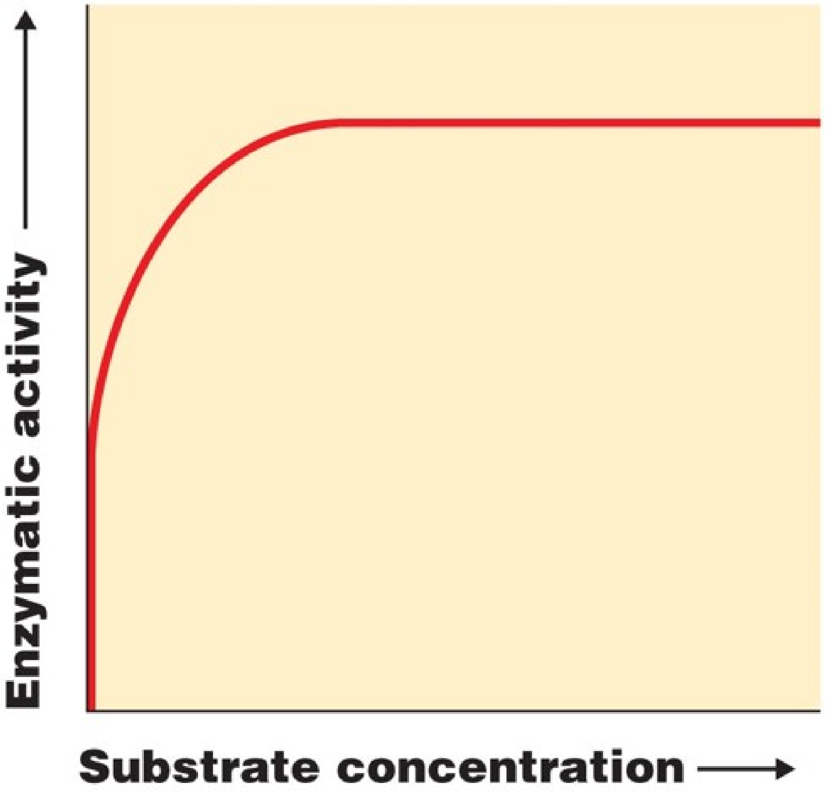


Figure 5.5c Factors that Influence Enzymatic Activity, Plotted for a Hypothetical Enzyme

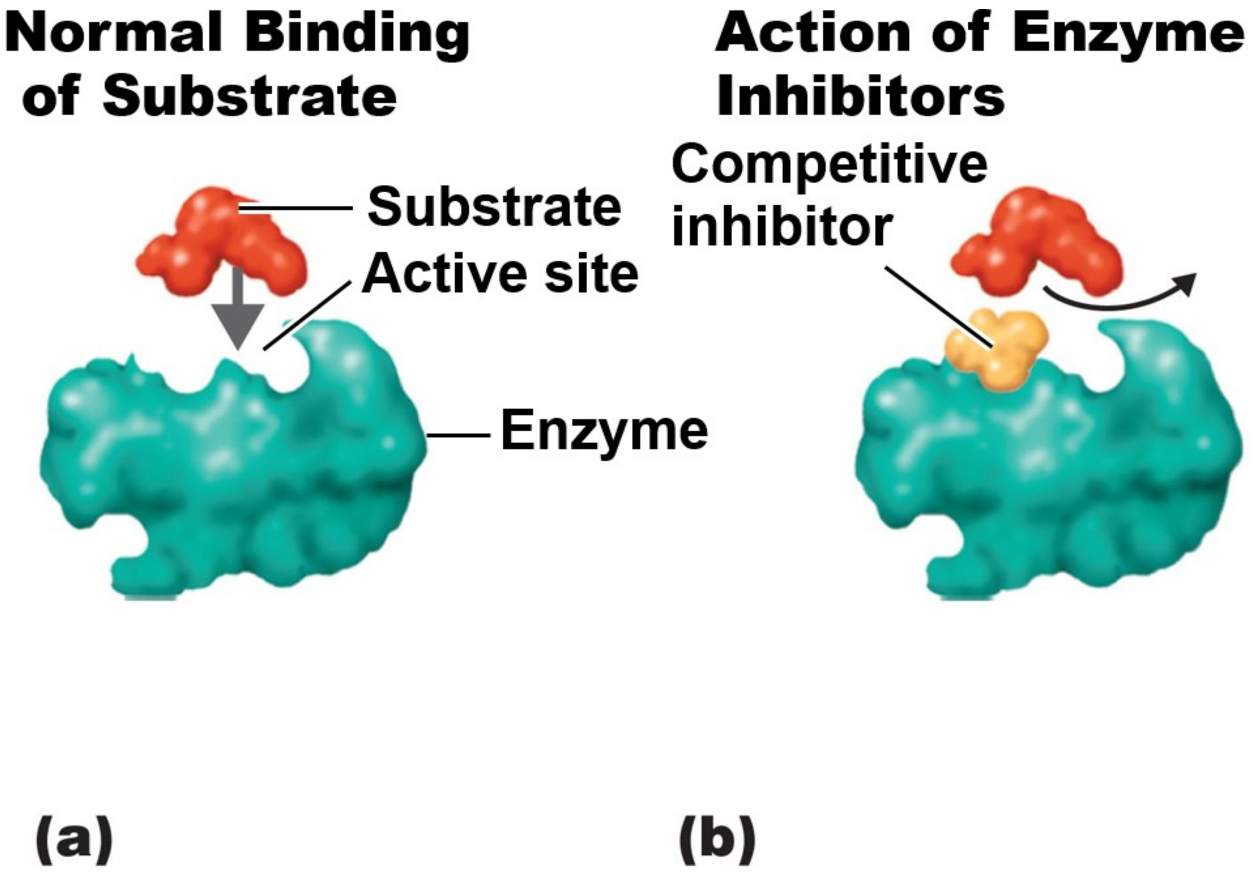
(c) Substrate concentration. With increasing concentration of substrate molecules, the rate of reaction increases until the active sites on all the enzyme molecules are filled, at which point the maximum rate of reaction is reached.



Inhibitors (1 of 2)

- **Competitive inhibitors** fill the active site of an enzyme and compete with the substrate

Figure 5.7a-b Enzyme Inhibitors



Enzymes: Competitive Inhibition

PLAY **Animation: Enzymes: Competitive Inhibition**

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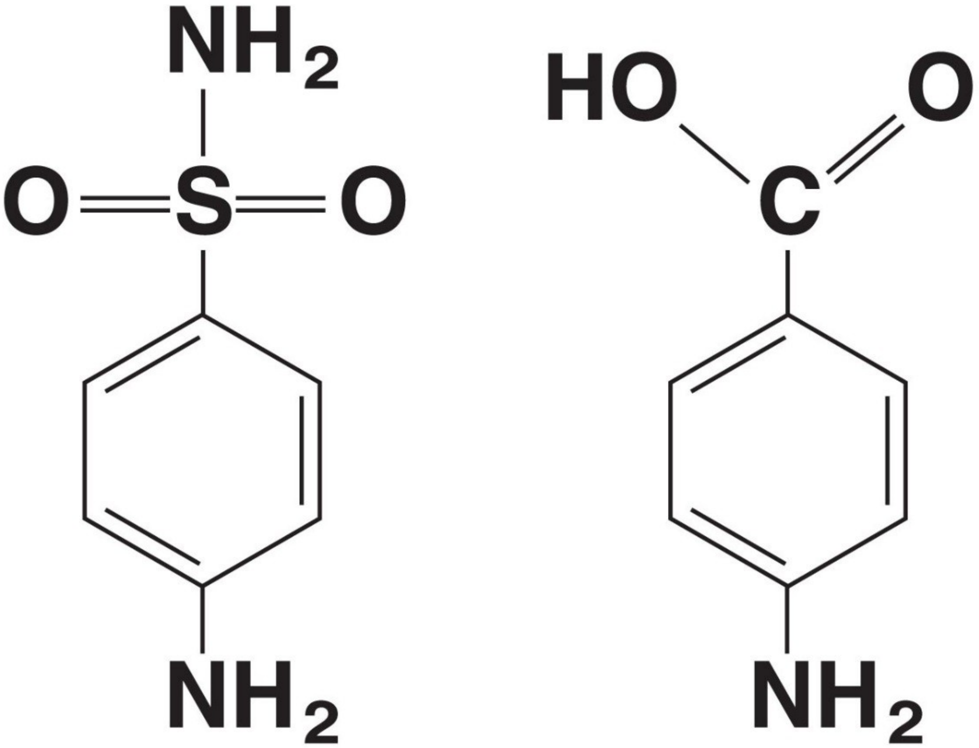


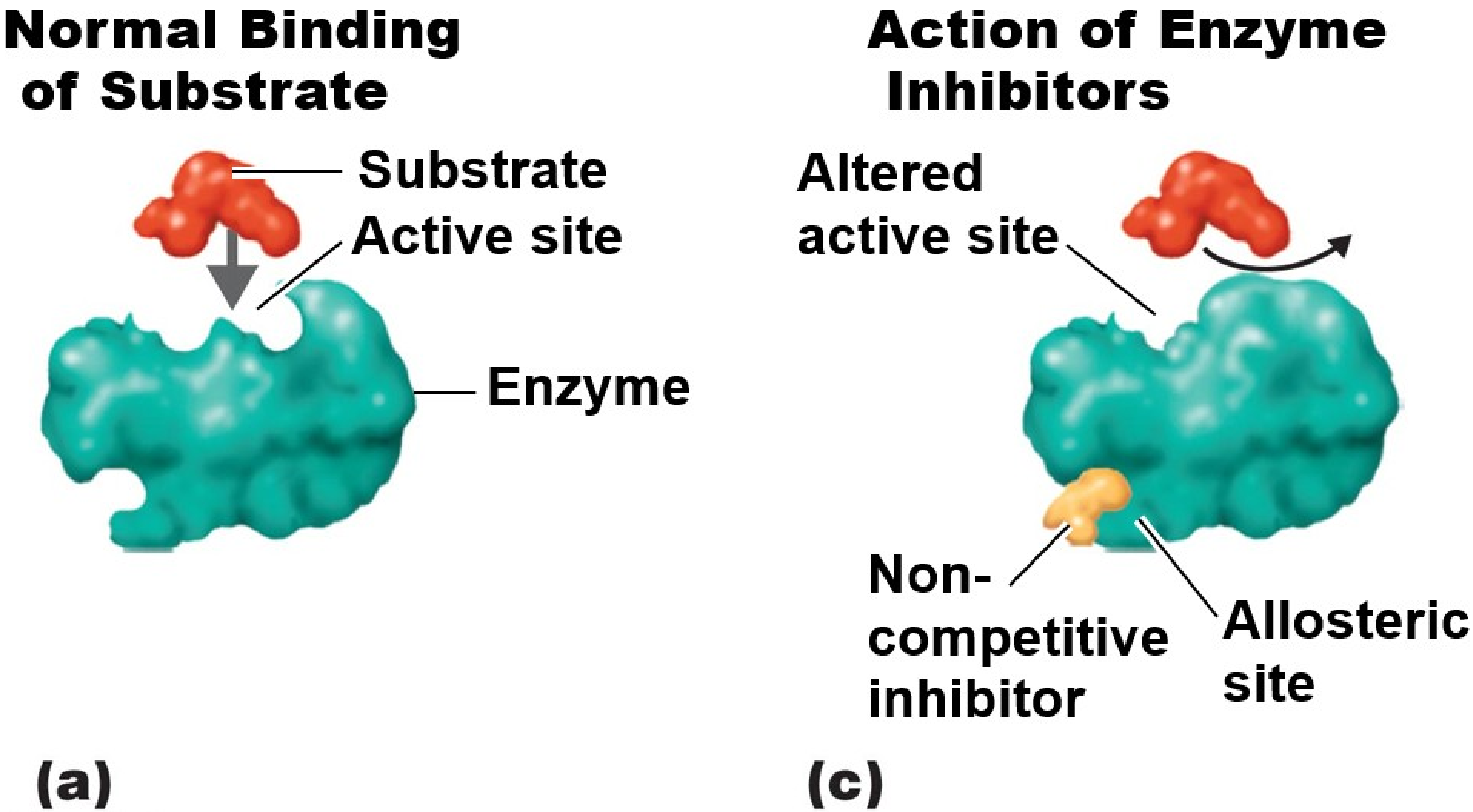
Sulfanilamide

PABA

Inhibitors (2 of 2)

- **Noncompetitive inhibitors** interact with another part of the enzyme (**allosteric site**) rather than the active site in a process called **allosteric inhibition**

Figure 5.7a-c Enzyme Inhibitors



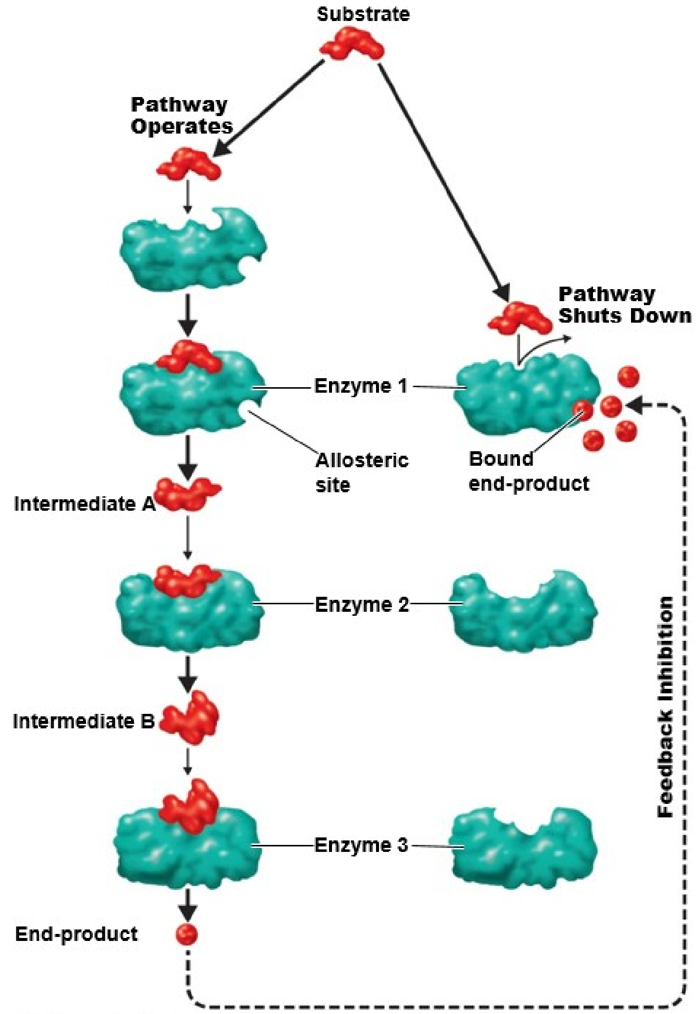
Enzymes: Non-Competitive Inhibition

PLAY **Animation: Enzymes: Non-Competitive Inhibition**

Feedback Inhibition

- End-product of a reaction allosterically inhibits enzymes from earlier in the pathway

Figure 5.8 Feedback Inhibition



Ribozymes

- RNA that function as catalysts by cutting and splicing RNA

Check Your Understanding-2

Check Your Understanding

- What is a coenzyme?
  5-3
- Why is enzyme specificity important?
  5-4
- What happens to an enzyme below its optimal temperature? Above its optimal temperature?
  5-5
- Why is feedback inhibition noncompetitive inhibition?
  5-6
- What is a ribozyme?
  5-7

Energy Production

Learning Objectives

5-8 Explain the term **oxidation-reduction**.

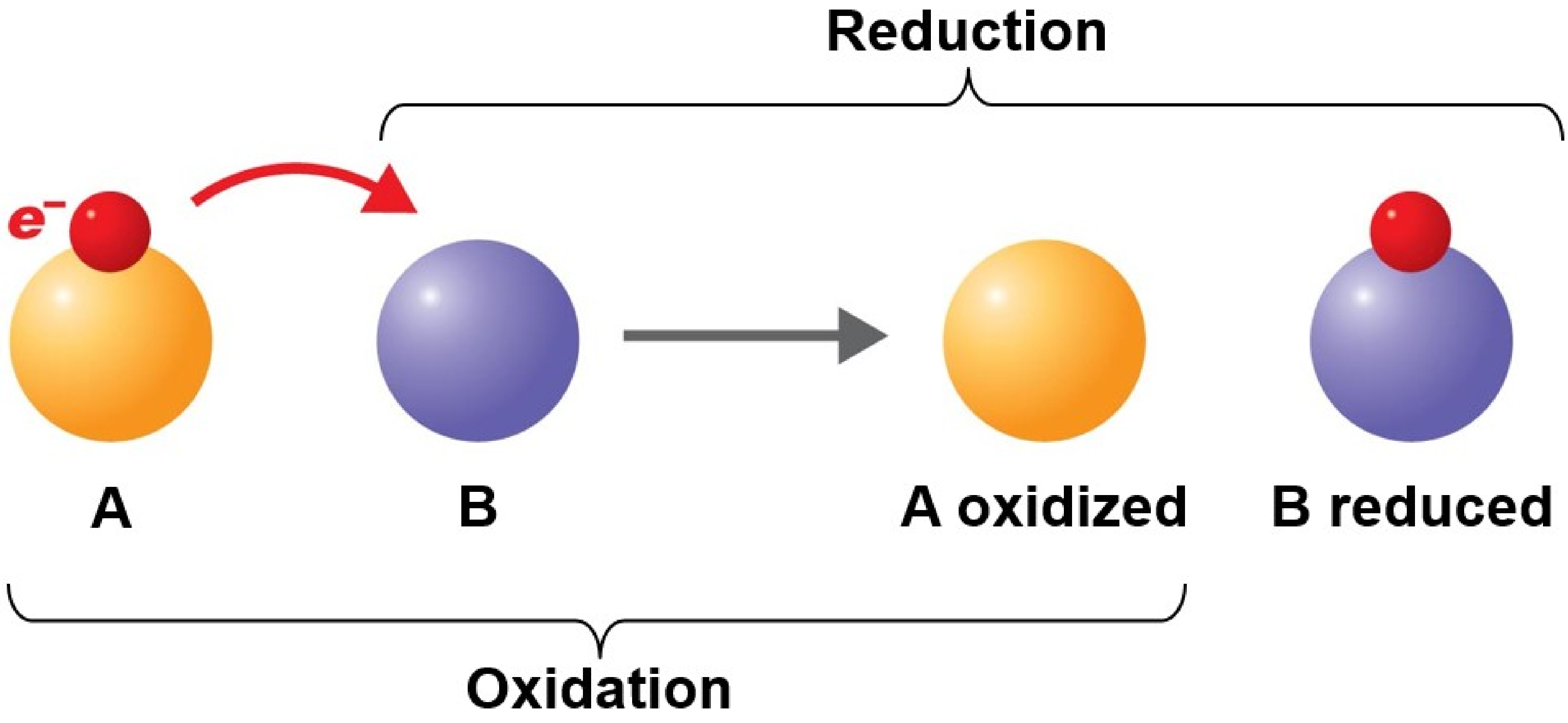
5-9 List and provide examples of three types of phosphorylation reactions that generate ATP.

5-10 Explain the overall function of metabolic pathways.

Oxidation-Reduction Reactions
(1 of 3)

- **Oxidation:** removal of electrons
- **Reduction:** gain of electrons
- **Redox reaction:** an oxidation reaction paired with a reduction reaction

Figure 5.9 Oxidation-Reduction



Oxidation-Reduction Reactions

(2 of 3)

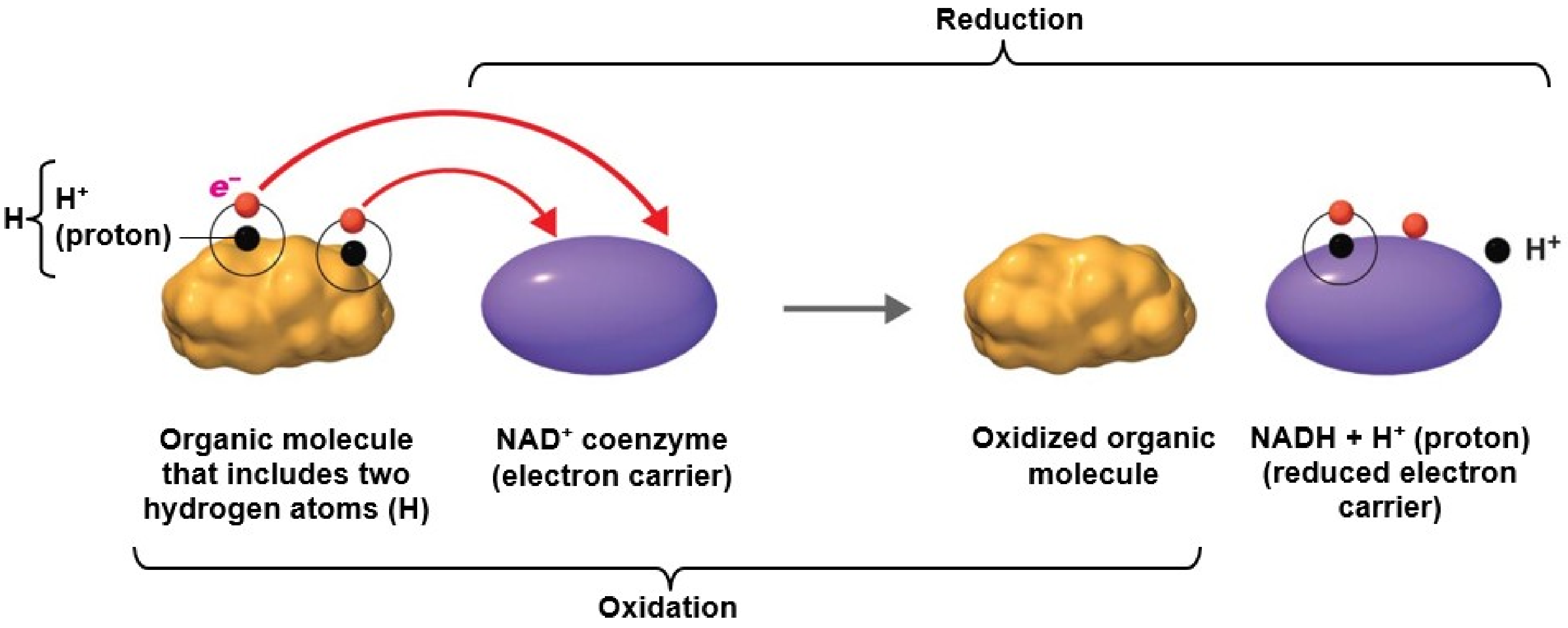
PLAY **Animation: Oxidation-Reduction Reactions**

Oxidation-Reduction Reactions

(3 of 3)

- In biological systems, electrons and protons are removed at the same time; equivalent to a hydrogen atom
- Biological oxidations are often **dehydrogenations**

Figure 5.10 Representative Biological Oxidation



Check Your Understanding-3

Check Your Understanding

- Why is glucose such an important molecule for organisms?
  5-8

The Generation of ATP

- ATP is generated by the **phosphorylation** of ADP with the input of energy

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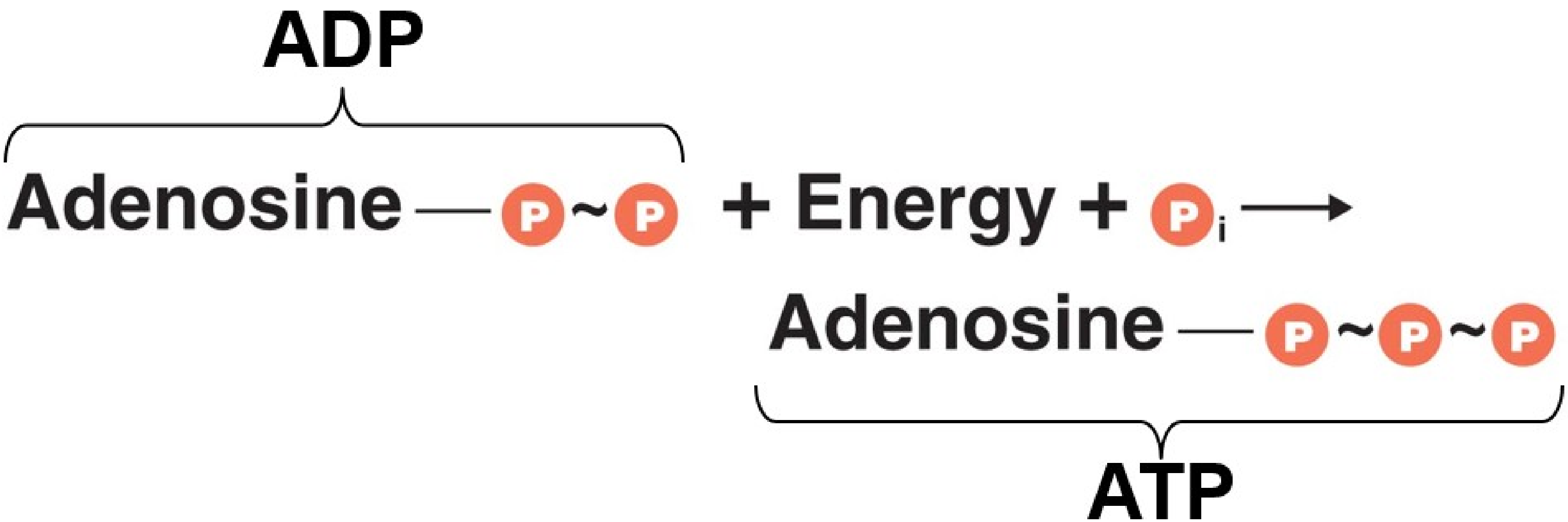

Substrate-Level Phosphorylation

- ATP generated when high-energy PO_4^- added to ADP generates ATP

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$$\mathrm{C{-}C{-}C} \sim \mathrm{P} + \mathrm{ADP} \rightarrow \mathrm{C{-}C{-}C} + \mathrm{ATP}$$

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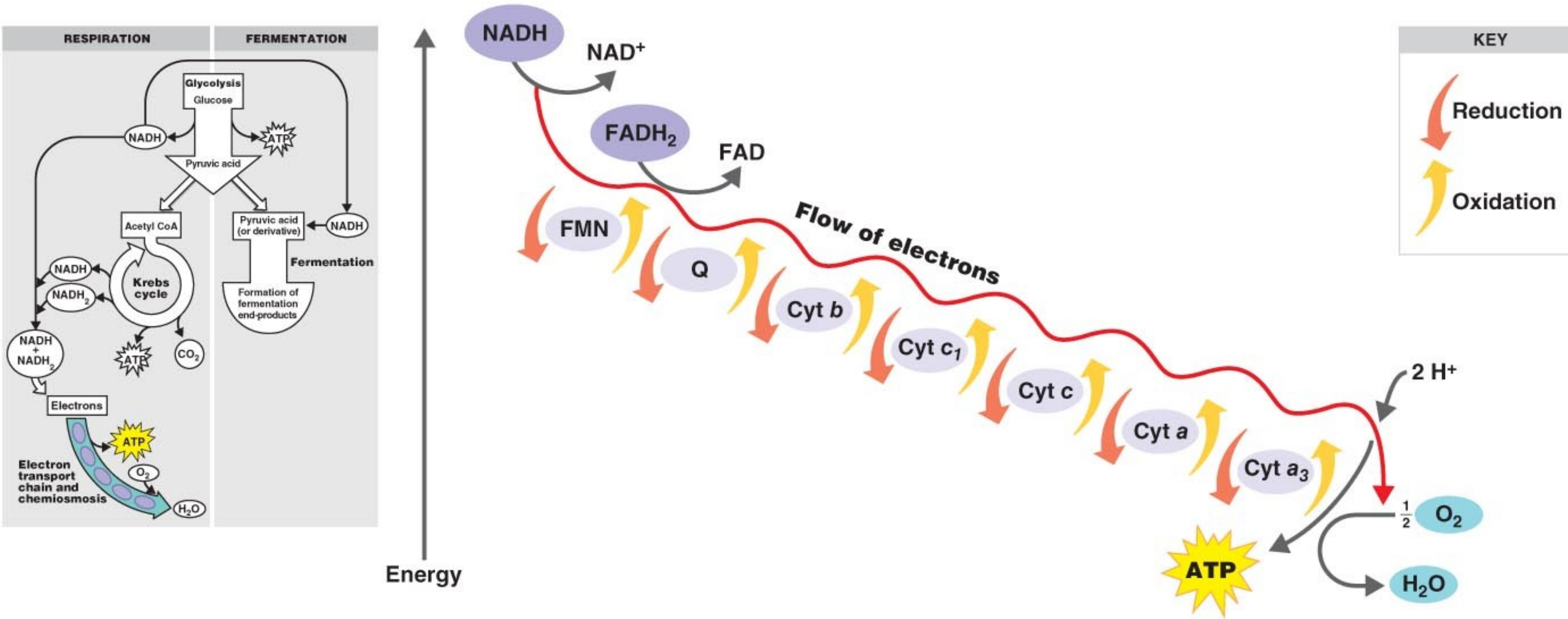
Oxidative Phosphorylation

- Electrons are transferred from one electron carrier to another along an **electron transport chain** (**system**) on a membrane that releases energy to generate ATP

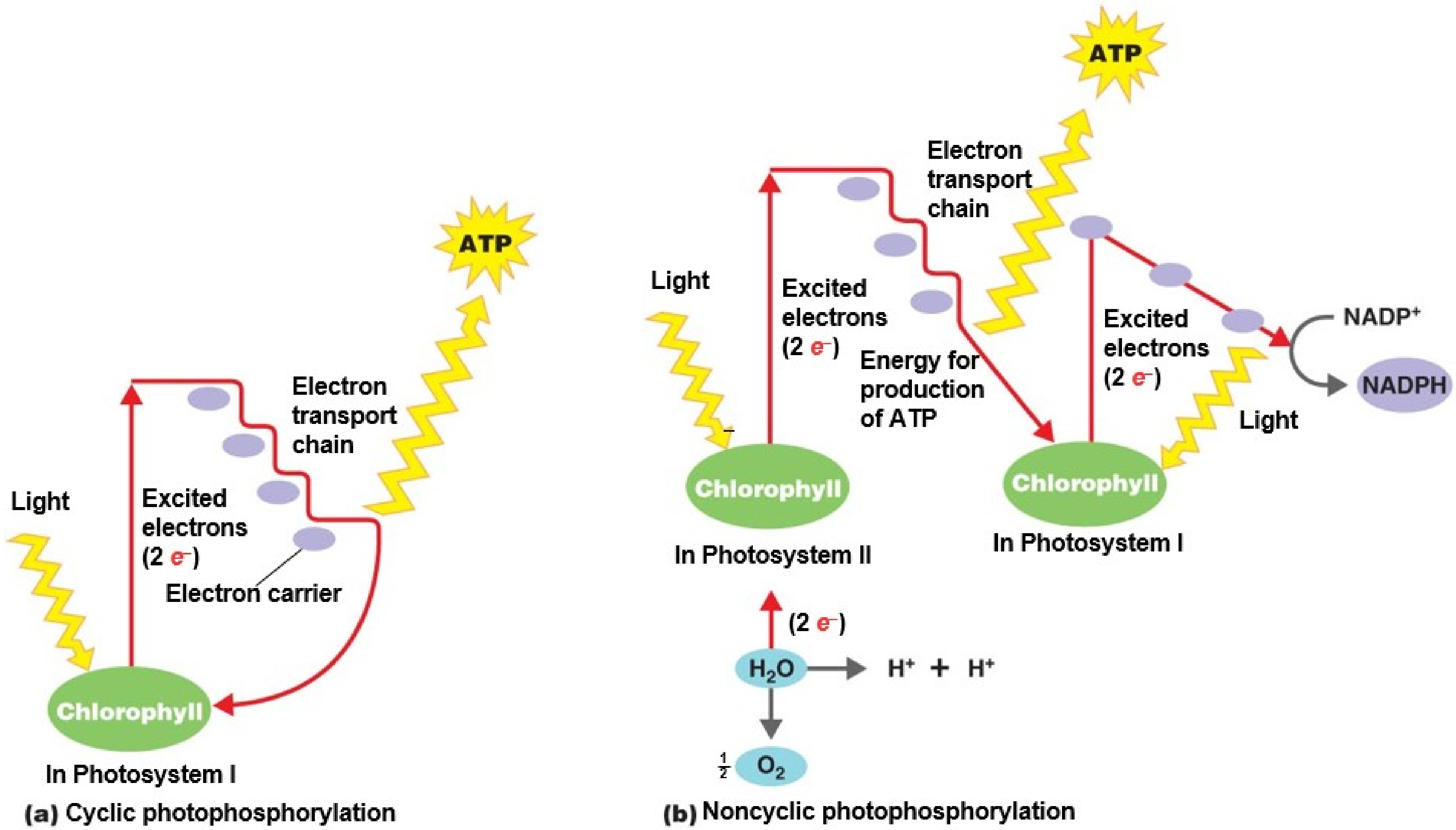
Figure 5.14 An Electron Transport Chain (System) (1 of 2)



Photophosphorylation

- Occurs only in light-trapping photosynthetic cells
- Light energy is converted to ATP when the transfer of electrons (oxidation) from chlorophyll pass through a system of carrier molecules

Figure 5.25 Photophosphorylation



Check Your Understanding-4

Check Your Understanding

- ✓ Outline the three ways that ATP is generated. 5-9

Metabolic Pathways of Energy Production

- Series of enzymatically catalyzed chemical reactions
- Extracts energy from organic compounds and stores it in chemical form (ATP)

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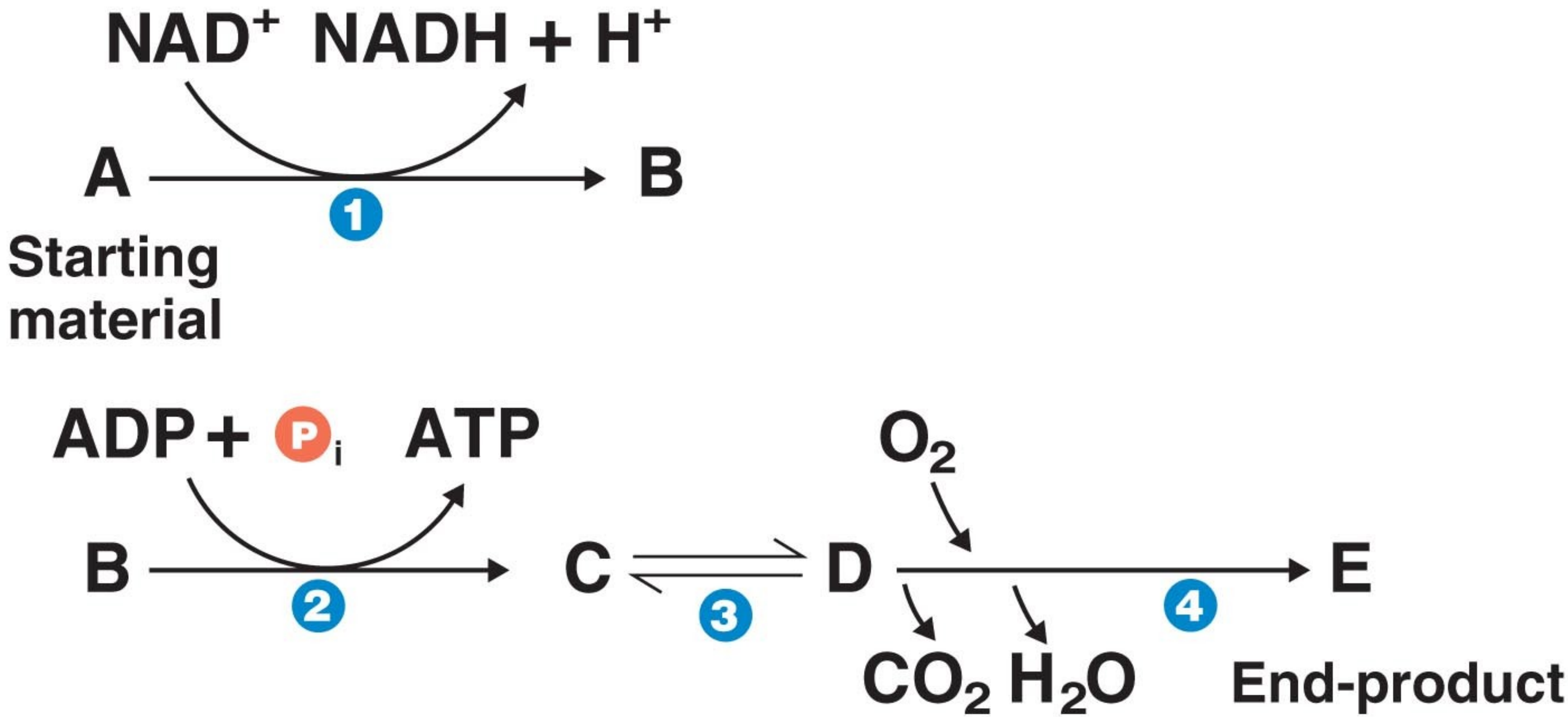


Check Your Understanding-5

Check Your Understanding

- ✓ What is the purpose of metabolic pathways? 5-10

Carbohydrate Catabolism (1 of 2)

Learning Objectives

5-11 Describe the chemical reactions of glycolysis.

5-12 Identify the functions of the pentose phosphate and Entner-Doudoroff pathways.

5-13 Explain the products of the Krebs cycle.

5-14 Describe the chemiosmotic model for ATP generation.

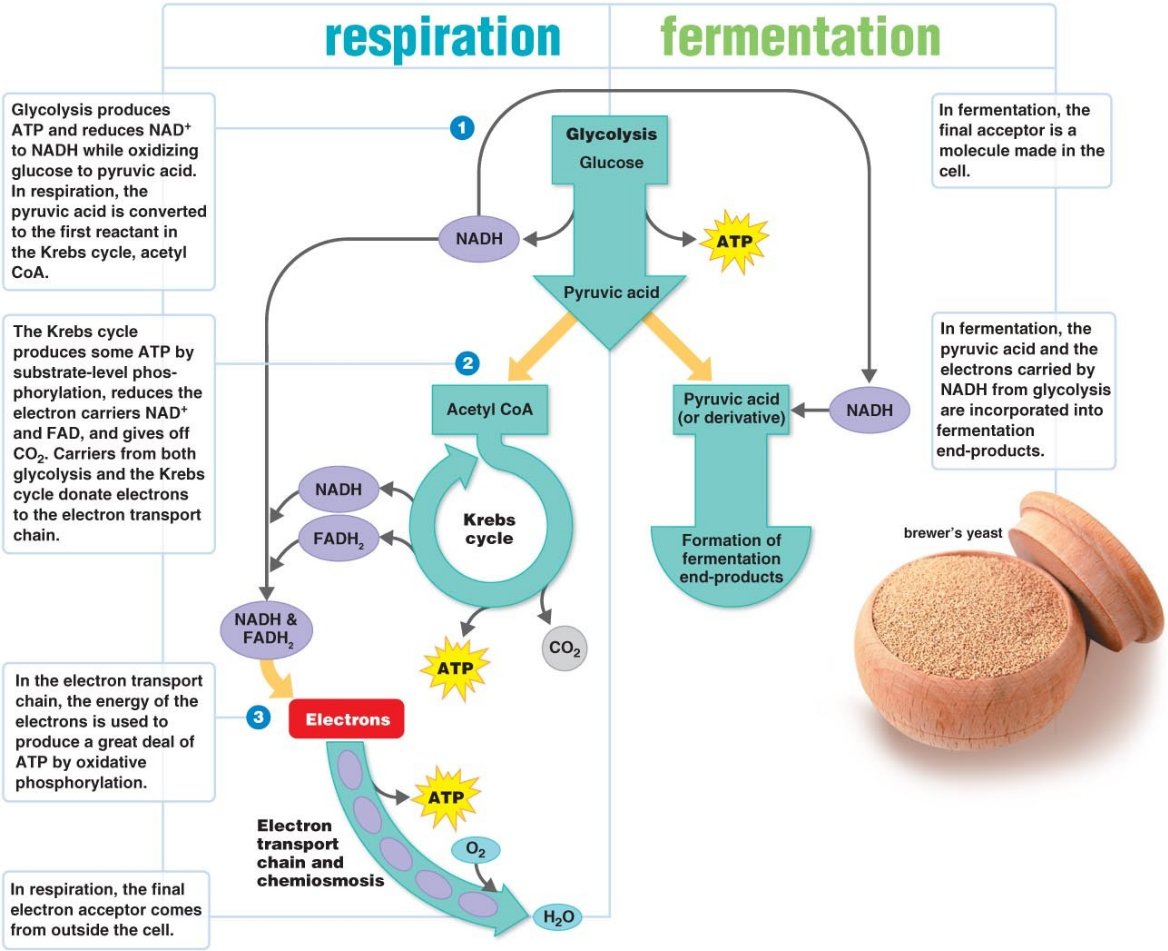
5-15 Compare and contrast aerobic and anaerobic respiration.

5-16 Describe the chemical reactions of, and list some products of, fermentation.

Carbohydrate Catabolism (2 of 2)

- The breakdown of carbohydrates to release energy
  - Glycolysis
  - Krebs cycle
  - Electron transport chain (system)

Figure 5.11 An Overview of Respiration and Fermentation (1 of 2)



Glycolysis (1 of 4)

- The oxidation of glucose to pyruvic acid produces ATP and NADH

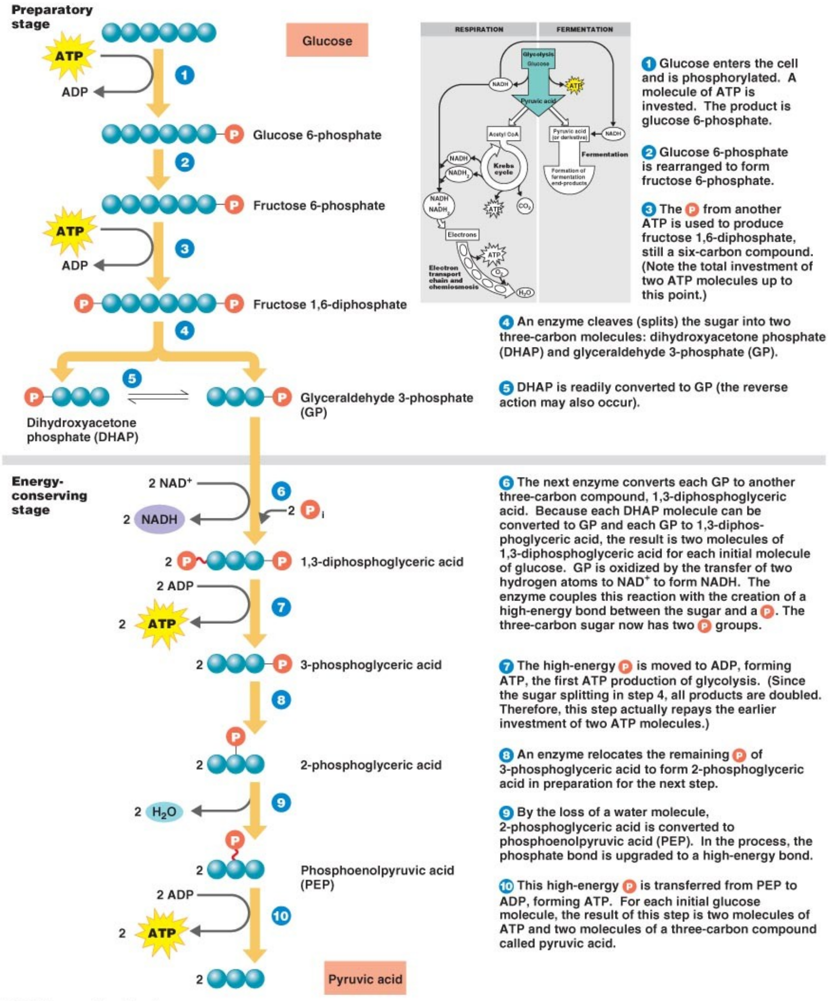
Glycolysis: Overview

PLAY **Animation: Glycolysis: Overview**

Glycolysis (2 of 4)

- Preparatory stage
  - 2 ATP are used
  - Glucose is split to form two molecules of glyceraldehyde 3-phosphate

Figure 5.12 An outline of the Reactions of Glycolysis (Embden-Meyerhof Pathway)



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Glycolysis (3 of 4)

- Energy-conserving stage
  - The two glyceraldehyde 3-phosphate molecules are oxidized to 2 pyruvic acid molecules
  - 4 ATP are produced
  - 2 NADH are produced

Glycolysis: Steps

PLAY **Animation: Glycolysis: Steps**

Glycolysis (4 of 4)

- $\text{Glucose} + 2\ \text{ATP} + 2\ \text{ADP} + 2\ \text{PO}_4^{-} + 2\ \text{NAD}^{+} \rightarrow 2$ $\text{pyruvic acid} + 4\ \text{ATP} + 2\ \text{NADH} + 2\text{H}^{+}$
- Overall **net gain** of two molecules of ATP for each molecule of glucose oxidized

Additional Pathways to Glycolysis

- **Pentose phosphate pathway**
  - Uses pentoses and produces NADPH
  - Operates simultaneously with glycolysis
- **Entner-Doudoroff pathway**
  - Produces NADPH and ATP
  - Does not involve glycolysis
  - Occurs in **Pseudomonas, Rhizobium**, and **Agrobacterium**

Check Your Understanding-6

Check Your Understanding

- ✓ What happens during the preparatory and energy-conserving stages of glycolysis?
  5-11
- ✓ What is the value of the pentose phosphate and Entner-Doudoroff pathways if they produce only one ATP molecule?
  5-12

Cellular Respiration

- Oxidation of molecules liberates electrons to operate an electron transport chain
- Final electron acceptor comes from outside the cell and is inorganic
- ATP is generated by oxidative phosphorylation

Aerobic Respiration (1 of 5)

- **Krebs cycle**
  - Pyruvic acid (from glycolysis) is oxidized and **decarboxylation** (loss of CO_2) occurs
  - The resulting two-carbon compound attaches to coenzyme A, forming acetyl CoA and NADH

Aerobic Respiration (2 of 5)

- **Krebs cycle**
  - Oxidation of acetyl CoA produces NADH, $FADH_2$, and ATP, and liberates CO_2 as waste

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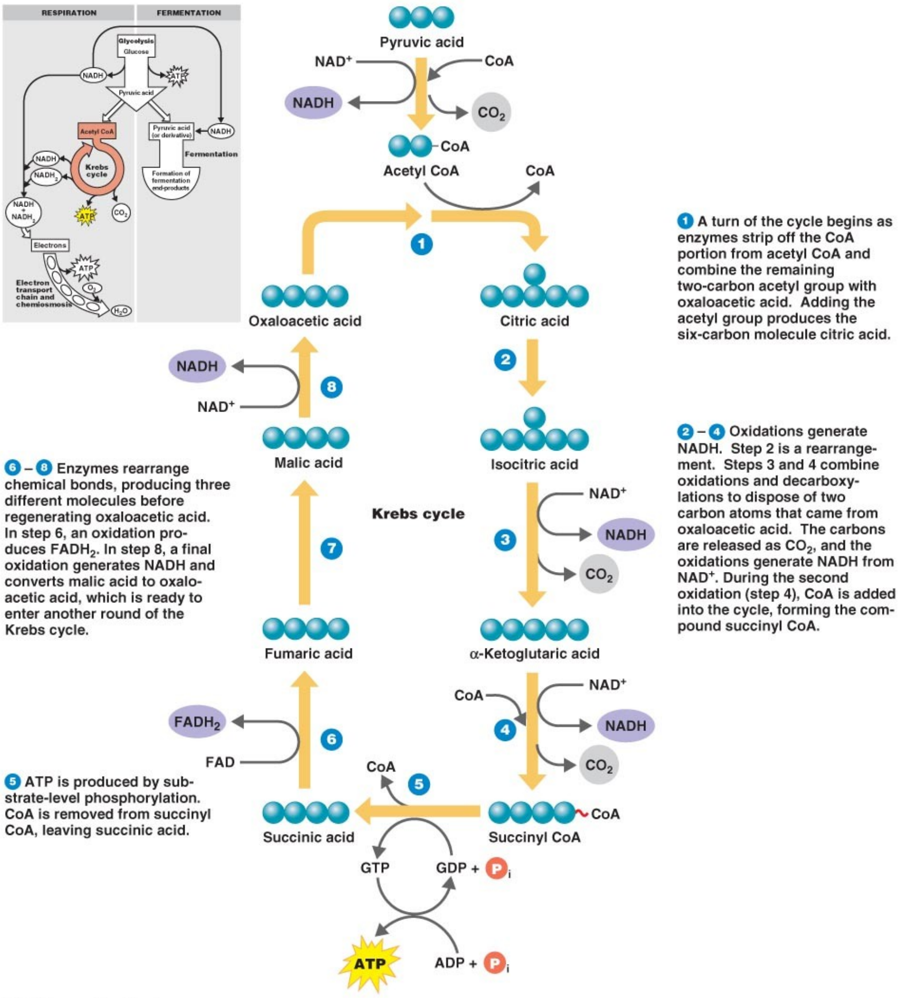
Krebs Cycle: Overview

PLAY **Animation: Krebs Cycle: Overview**

Figure 5.13 The Krebs Cycle



Krebs Cycle: Steps

PLAY **Animation: Krebs Cycle: Steps**

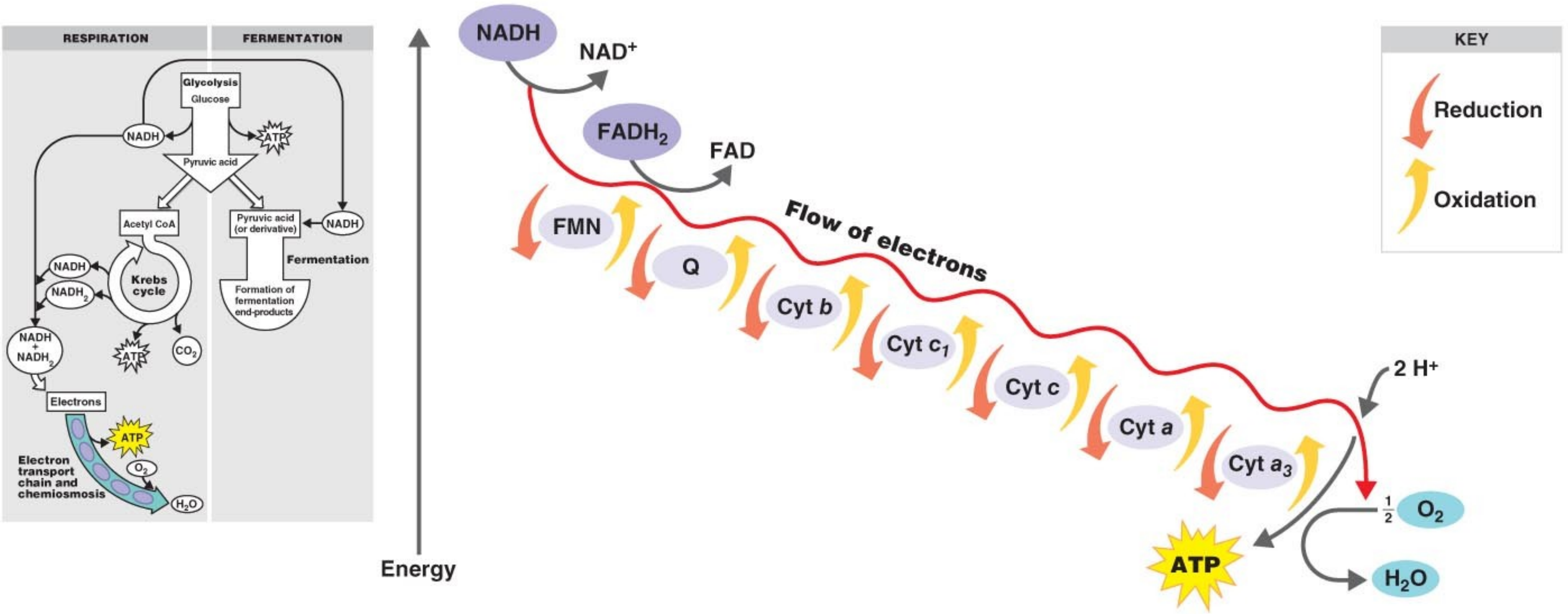
Aerobic Respiration (3 of 5)

- **Electron transport chain (system)**
  - Occurs in the plasma membrane of prokaryotes; inner mitochondrial membrane of eukaryotes
  - Series of carrier molecules (**flavoproteins, cytochromes,** and **ubiquinones**) are oxidized and reduced as electrons are passed down the chain
  - Energy released is used to produce ATP by **chemiosmosis**

Electron Transport Chain: Overview

PLAY **Animation: Electron Transport Chain: Overview**

Figure 5.14 An Electron Transport Chain (System) (2 of 2)



Aerobic Respiration (4 of 5)

- Chemiosmosis
  - Electrons (from NADH) pass down the electron transport chain while protons are pumped across the membrane
    - Establishes proton gradient (proton motive force)
  - Protons in higher concentration on one side of the membrane diffuse through ATP synthase
    - Releases energy to synthesize ATP

Figure 5.16 Electron Transport and the Chemiosmotic Generation of ATP

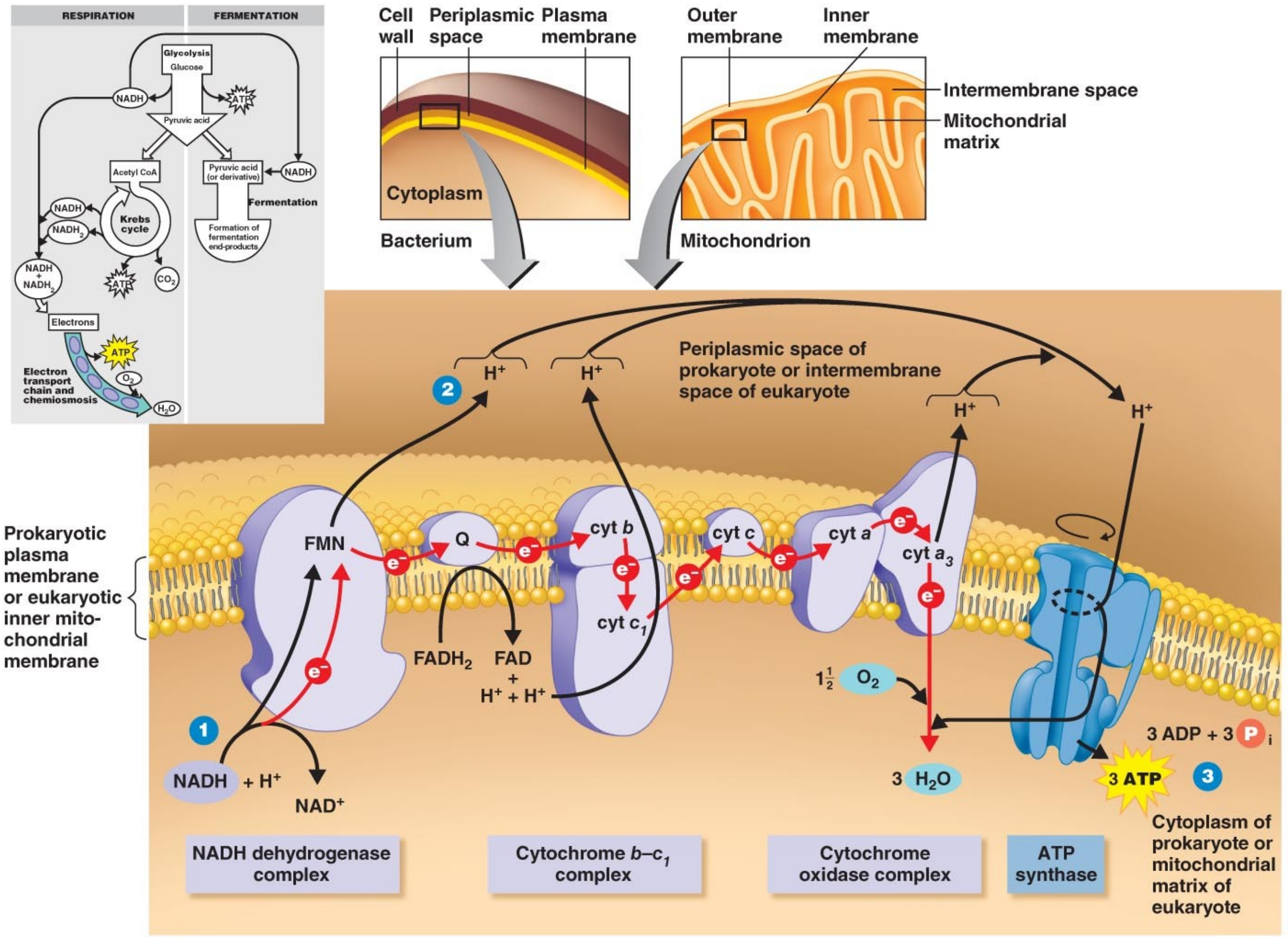
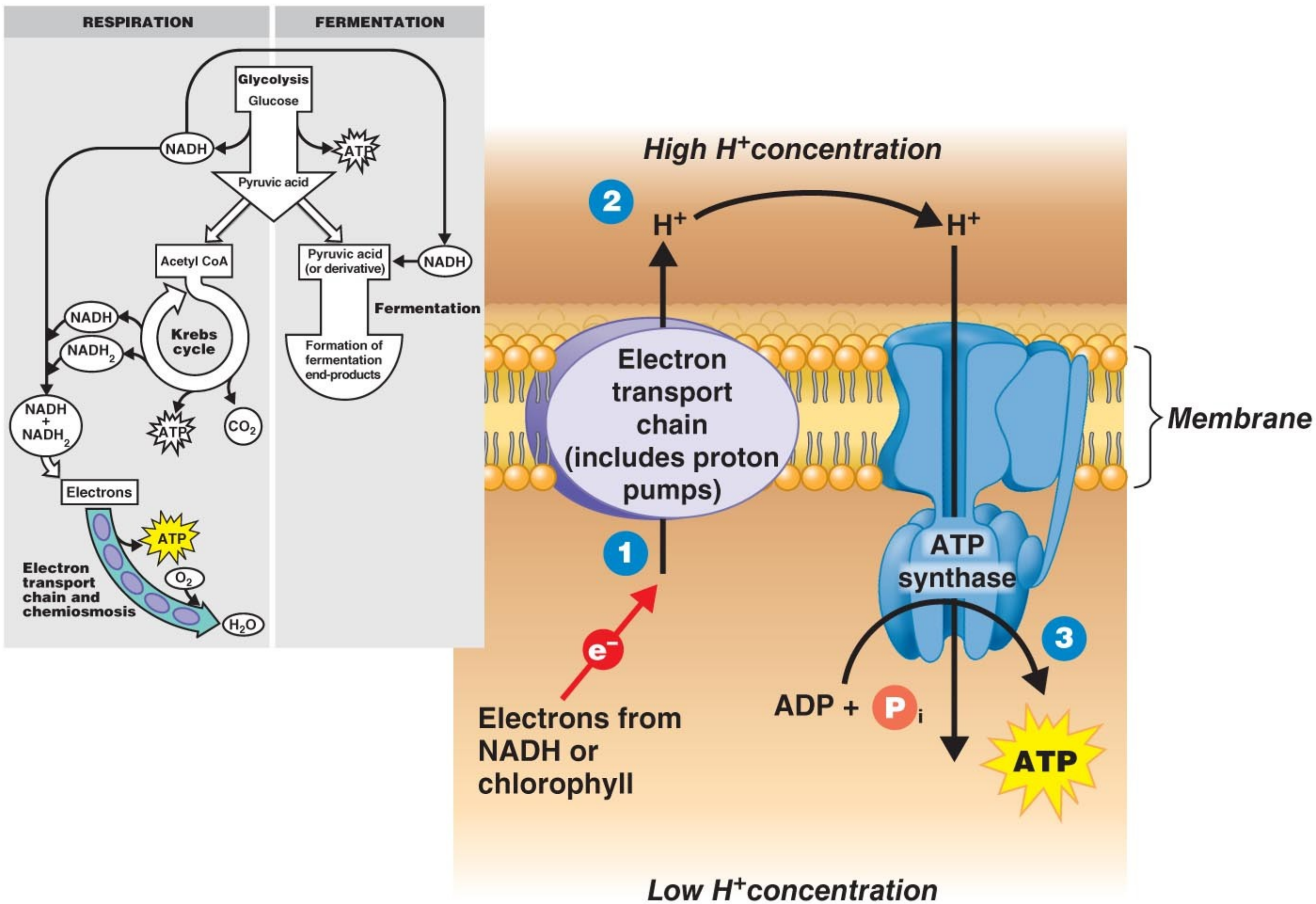


Figure 5.15 Chemiosmosis



Aerobic Respiration (5 of 5)

- The final electron acceptor in the electron transport chain is molecular oxygen (O_2)

Unnumbered Figure pg. 126

$$C_6H_{12}O_6 + 6\ O_2 + 38\ ADP + 38\ P_i \longrightarrow 6\ CO_2 + 6\ H_2O + 38\ ATP$$

Glucose Oxygen

Carbon dioxide Water

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Carbohydrate Catabolism

- Each NADH can be oxidized in the electron transport chain to produce 3 molecules of ATP
- Each $FADH_2$ can produce 2 molecules of ATP

Anaerobic Respiration (1 of 2)

- The final electron acceptor in the electron transport chain is NOT O_2
  - Yields less energy than aerobic respiration

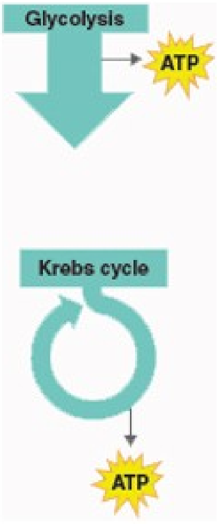
Anaerobic Respiration (2 of 2)

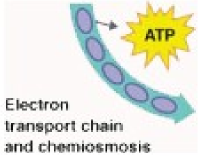
Electron Acceptor	Products
NO_3^-	NO_2^-, N_2 + H_2O
SO_4^-	H_2S + H_2O
CO_3^{2-}	CH_4 + H_2O

Table 5.3 ATP Yield During Prokaryotic Aerobic Respiration of One Glucose Molecule

TABLE 5.3 ATP Yield during Prokaryotic Aerobic Respiration of One Glucose Molecule

Source	ATP Yield (Method)
Glycolysis	
1. Oxidation of glucose to pyruvic acid	2 ATP (substrate-level phosphorylation)
2. Production of 2 NADH	6 ATP (oxidative phosphorylation in electron transport chain)
Preparatory Step	
1. Formation of acetyl CoA produces 2 NADH	6 ATP (oxidative phosphorylation in electron transport chain)
Krebs Cycle	
1. Oxidation of succinyl CoA to succinic acid	2 GTP (equivalent of AT P; substrate-level phosphorylation)
2. Production of 6 NADH	18 ATP (oxidative phosphorylation in electron transport chain)
3. Production of 2 FADH	4 ATP (oxidative phosphorylation in electron transport chain)
	Total: 38 ATP





Check Your Understanding-7

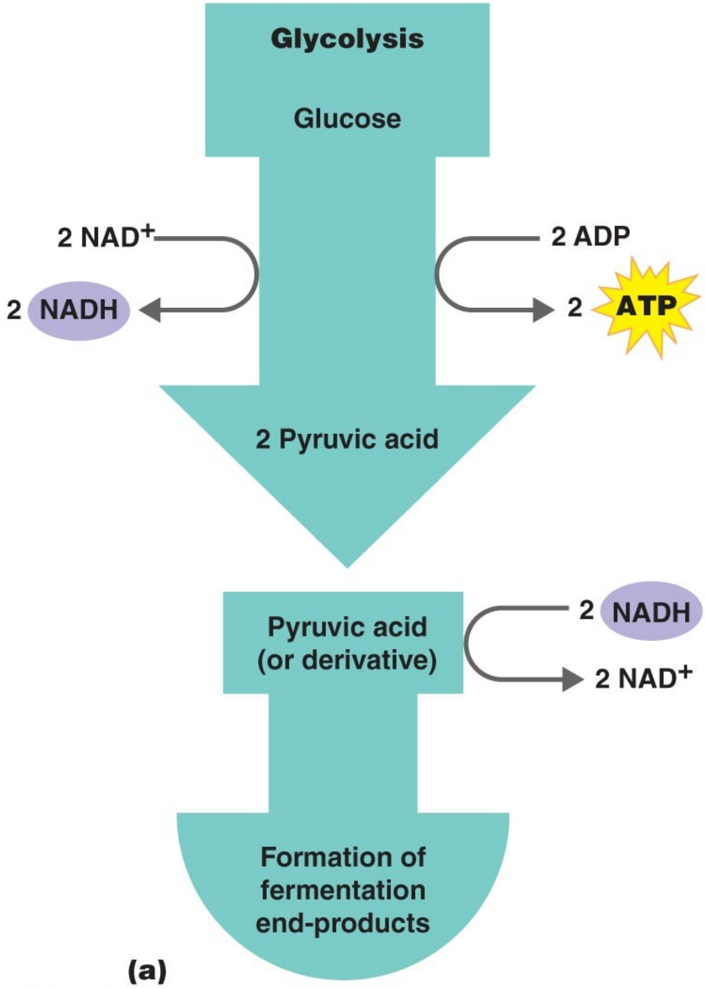
Check Your Understanding

- ✓ What are the principal products of the Krebs cycle?
  5-13
- ✓ How do carrier molecules function in the electron transport chain?
  5-14
- ✓ Compare the energy yield (ATP) of aerobic and anaerobic respiration.
  5-15

Fermentation (1 of 3)

- Releases energy from the oxidation of organic molecules
- Does not require oxygen
- Does not use the Krebs cycle or ETC
- Uses an organic molecule as the final electron acceptor
- Produces only small amounts of ATP

Figure 5.18a Fermentation



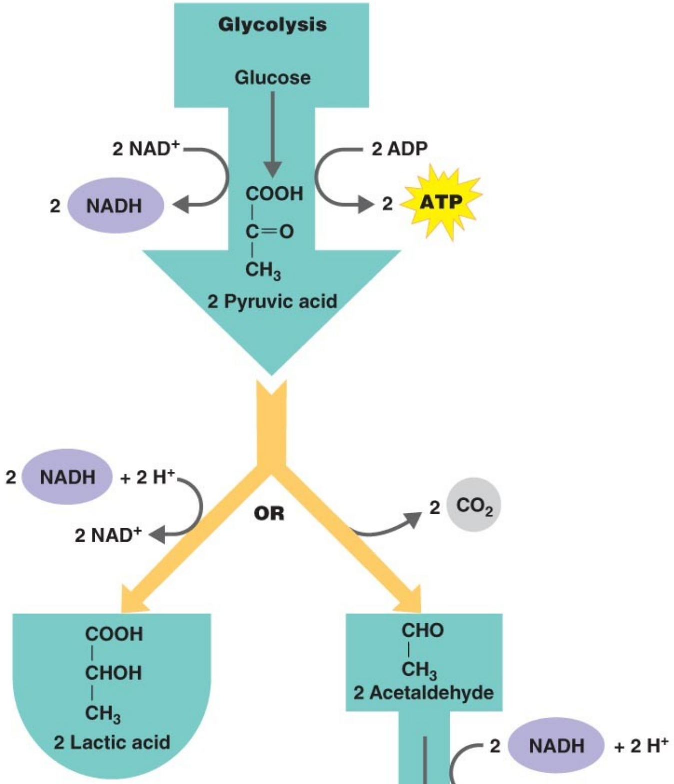
Fermentation (2 of 3)

- **Lactic acid fermentation:** produces lactic acid
  - **Homolactic fermentation:** produces lactic acid only
  - **Heterolactic fermentation:** produces lactic acid and other compounds
- Glucose is oxidized to pyruvic acid, which is then reduced by NADH

Fermentation (3 of 3)

- **Alcohol fermentation**: produces ethanol + CO_2
- Glucose is oxidized to pyruvic acid; pyruvic acid is converted to acetaldehyde and CO_2; NADH reduces acetaldehyde to ethanol

Figure 5.19 Types of Fermentation



(a) Lactic acid fermentation

(b) Alcohol fermentation

Figure 5.18b Fermentation

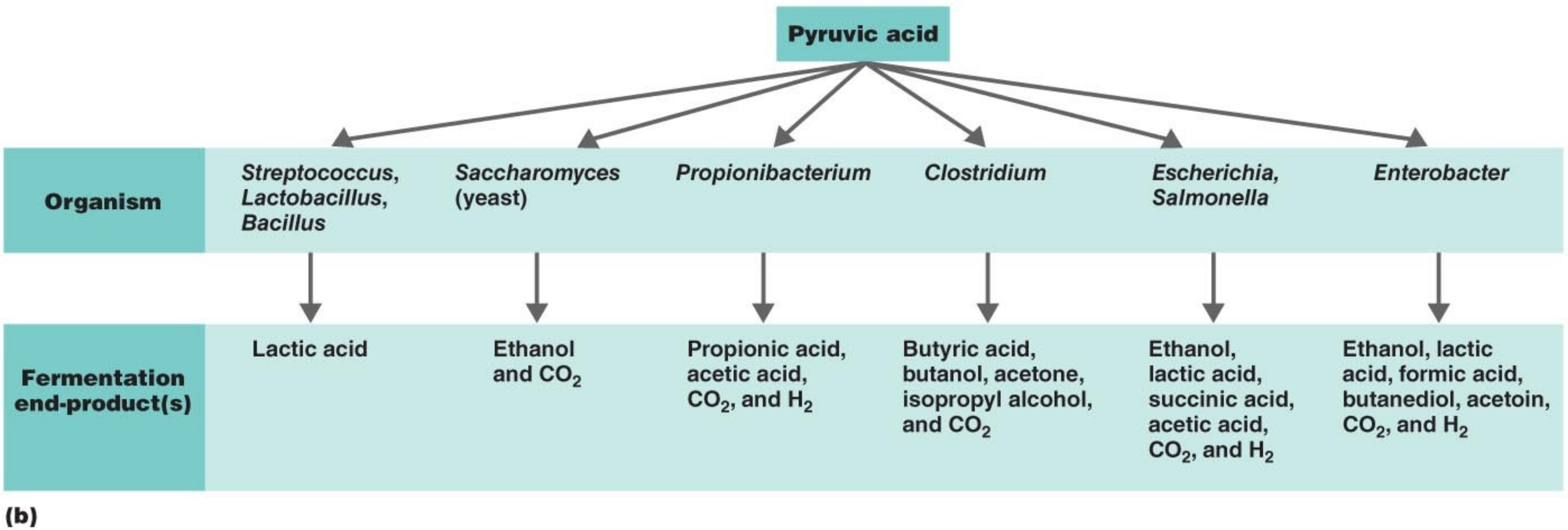


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Table 5.4 Some Industrial Uses for Different Types of Fermentations* (1 of 2)

TABLE 5.4 Some Industrial Uses for Different Types of Fermentations*

Fermentation End-Product(s)	Industrial or Commercial Use	Starting Material	Microorganism
Ethanol	Beer, wine	Starch, sugar	**Saccharomyces cerevisiae** (yeast, a fungus)
	Fuel	Agricultural wastes	**Saccharomyces cerevisiae** (yeast)
Acetic Acid	Vinegar	Ethanol	**Acetobacter**
Lactic Acid	Cheese, yogurt	Milk	**Lactobacillus, Streptococcus**
	Rye bread	Grain, sugar	**Lactobacillus delbrueckii**
	Sauerkraut	Cabbage	**Lactobacillus plantarum**
	Summer sausage	Meat	**Pediococcus**

Table 5.4 Some Industrial Uses for Different Types of Fermentations* (2 of 2)

Fermentation End-Product(s)	Industrial or Commercial Use	Starting Material	Microorganism
Propionic Acid and Carbon Dioxide	Swiss cheese	Lactic acid	**Propionibacterium freudenreichii**
Acetone and Butanol	Pharmaceutical, industrial uses	Molasses	**Clostridium acetobutylicum**
Citric Acid	Flavoring	Molasses	**Aspergillus (fungus)**
Methane	Fuel	Acetic acid	**Methanosarcina (archaeon)**
Sorbose	Vitamin C (ascorbic acid)	Sorbitol	**Gluconobacter**

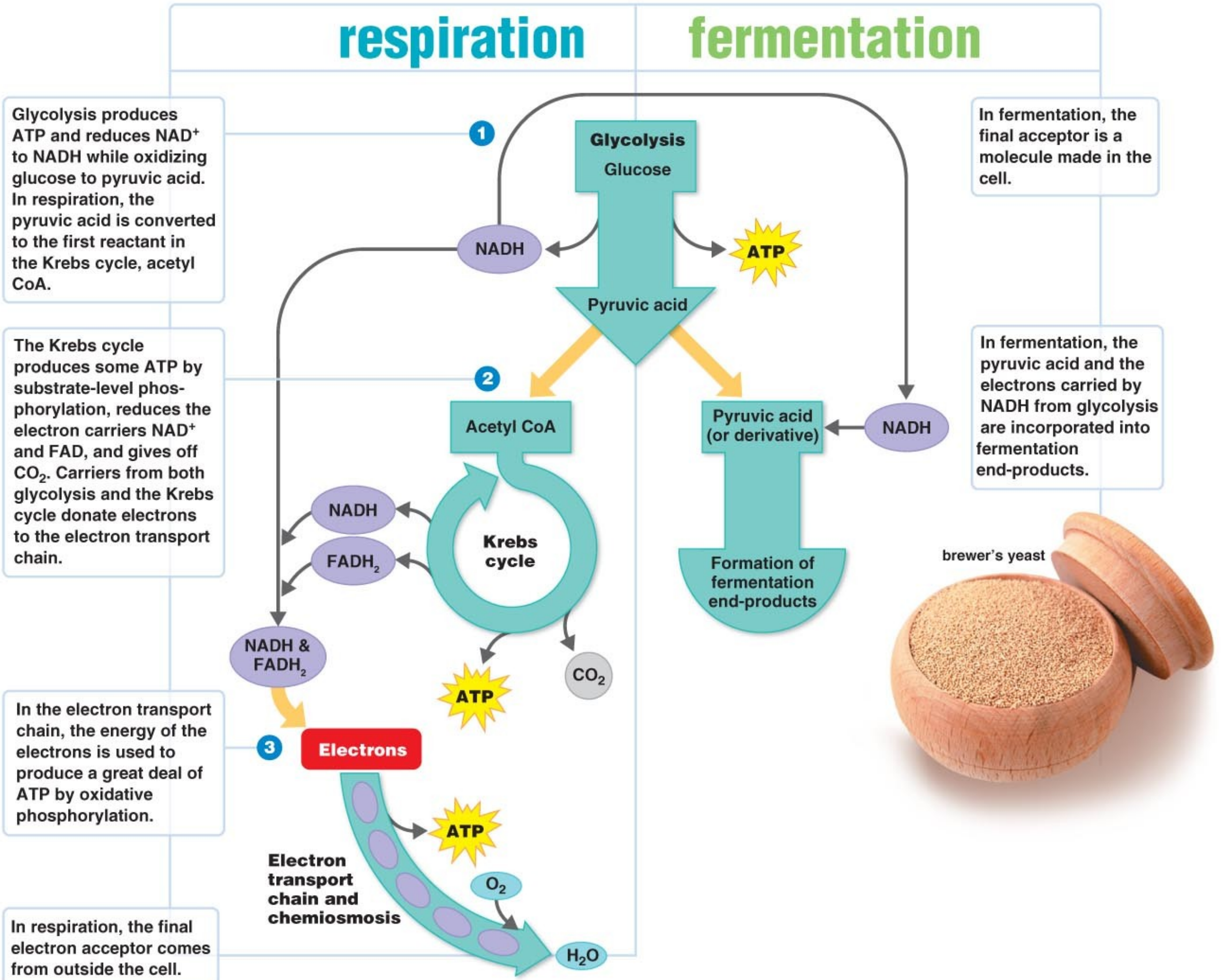
*Unless otherwise noted, the microorganisms listed are bacteria.

Check Your Understanding-8

Check Your Understanding

- ✓ List four compounds that can be made from pyruvic acid by an organism that uses fermentation.
  5-16

Figure 5.11 An Overview of Respiration and Fermentation (2 of 2)



Lipid and Protein Catabolism (1 of 2)

Learning Objective

5-17 Describe how lipids and proteins undergo catabolism.

Lipid and Protein Catabolism (2 of 2)

$$\text{Protein} \xrightarrow{\text{Extracellular proteases}} \text{Amino acids}$$

$$\xrightarrow[\text{dehydrogenation, desulfurization}]{\text{Deamination, decarboxylation,}} \text{Organic acid} \rightarrow \text{Krebs cycle}$$

Figure 5.20 Lipid Catabolism

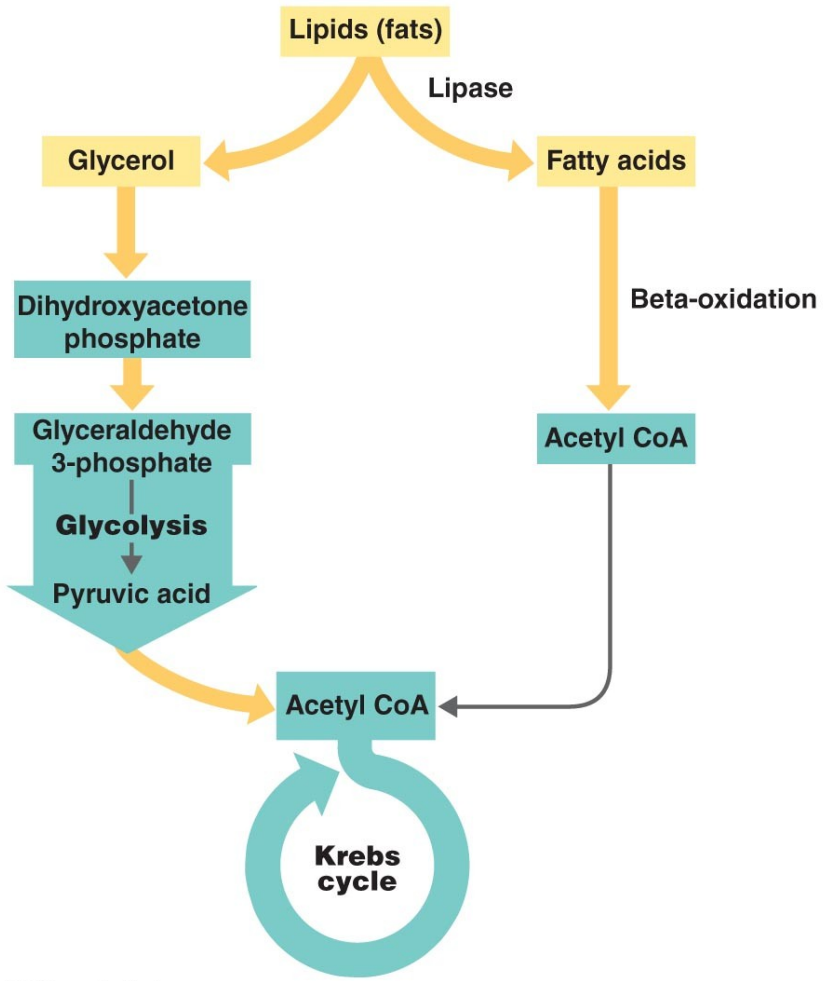
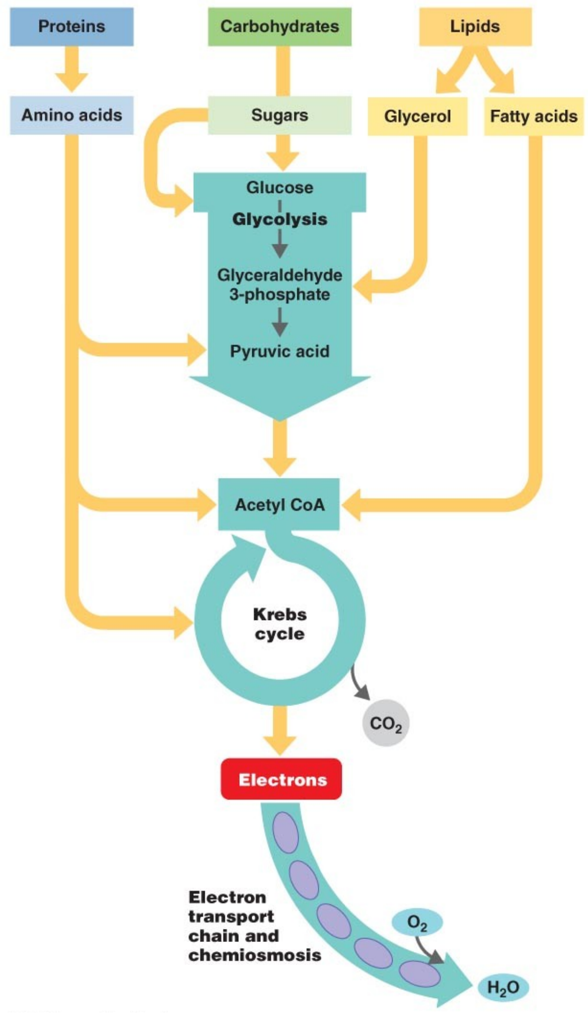


Figure 5.21 Catabolism of Various Organic Food Molecules



Check Your Understanding-9

Check Your Understanding

- ✓ What are the end-products of lipid and protein catabolism?
  5-17

Biochemical Tests and Bacterial Identification (1 of 3)

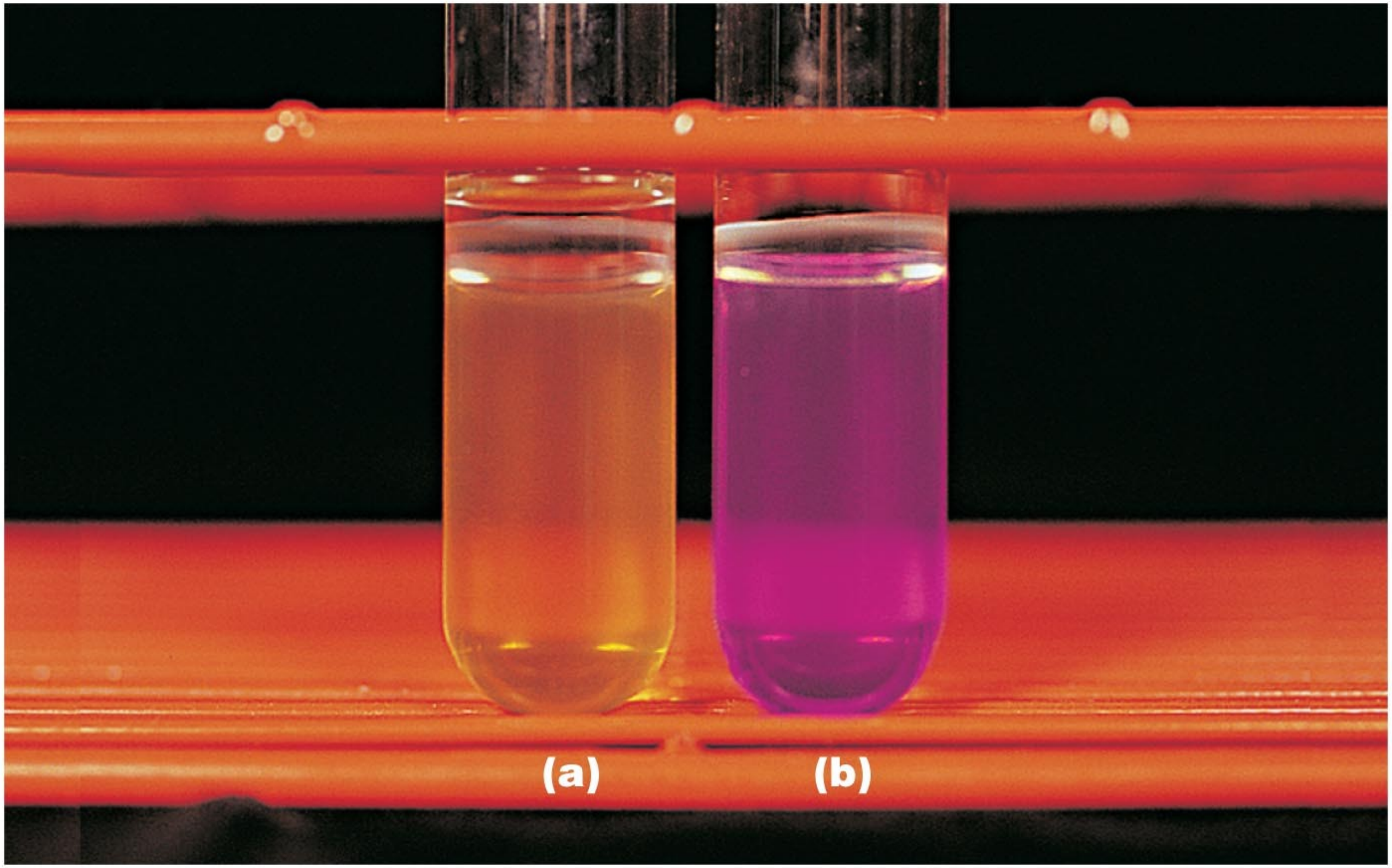
Learning Objective

5-18 Provide two examples of the use of biochemical tests to identify bacteria in the laboratory.

Biochemical Tests and Bacterial Identification (2 of 3)

- Biochemical tests identify bacteria by detecting enzymes (e.g., those involved in decarboxylation and dehydrogenation)

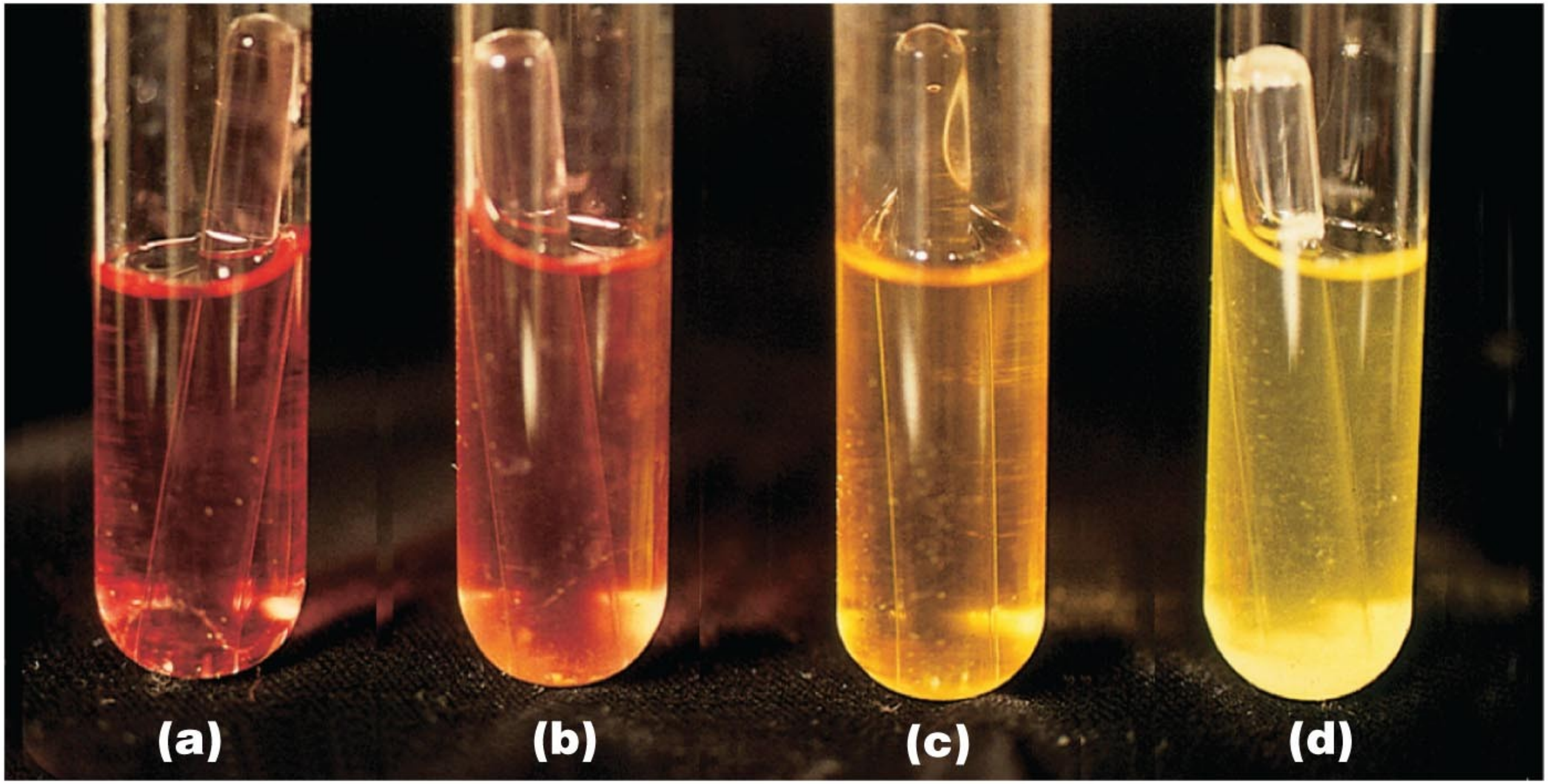
Figure 5.22 Detecting Amino Acid Catabolizing Enzymes in the Lab



Biochemical Tests and Bacterial Identification (3 of 3)

- **Fermentation test:** bacteria that catabolize carbohydrate or protein produce acid, causing the pH indicator to change color
- Oxidase test: identifies bacteria that have cytochrome oxidase (e.g., ***Pseudomonas***)

Figure 5.23 A Fermentation Test



Check Your Understanding-10

Check Your Understanding

- ✓ On what biochemical basis are **Pseudomonas** and **Escherichia** differentiated?
  5-18

Photosynthesis (1 of 3)

Learning Objectives

5-19 Compare and contrast cyclic and noncyclic photophosphorylation.

5-20 Compare and contrast the light-dependent and light-independent reactions of photosynthesis.

5-21 Compare and contrast oxidative phosphorylation and photophosphorylation.

Photosynthesis (2 of 3)

- **Light-dependent (light) reactions:** conversion of light energy into chemical energy (ATP and NADPH)
- **Light-independent (dark) reactions:** ATP and NADPH are used to reduce CO_2 to sugar (**carbon fixation**) via the Calvin-Benson cycle

Photosynthesis: Overview

PLAY **Animation: Photosynthesis: Overview**

Photosynthesis (3 of 3)

- Oxygenic:

$$6\,CO_2 + 12\,H_2O + \text{Light energy} \rightarrow C_6H_{12}O_6 + 6\,H_2O + 6\,O_2$$

- Anoxygenic:

$$6\,CO_2 + 12\,H_2S + \text{Light energy} \rightarrow C_6H_{12}O_6 + 6\,H_2O + 12\,S$$

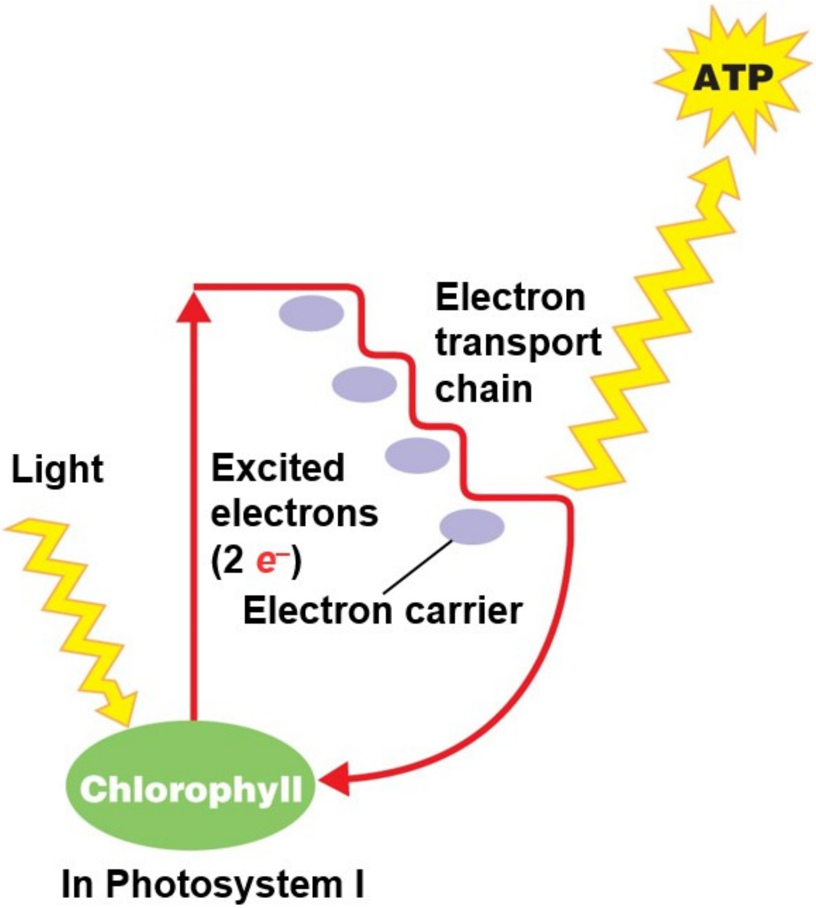
Photosynthesis: Comparing Prokaryotes and Eukaryotes

PLAY **Animation: Photosynthesis: Comparing Prokaryotes and Eukaryotes**

Photosynthesis: Light Reaction: Cyclic Photophosphorylation

PLAY **Animation: Photosynthesis: Light Reaction: Cyclic Photophosphorylation**

Figure 5.25a Photophosphorylation

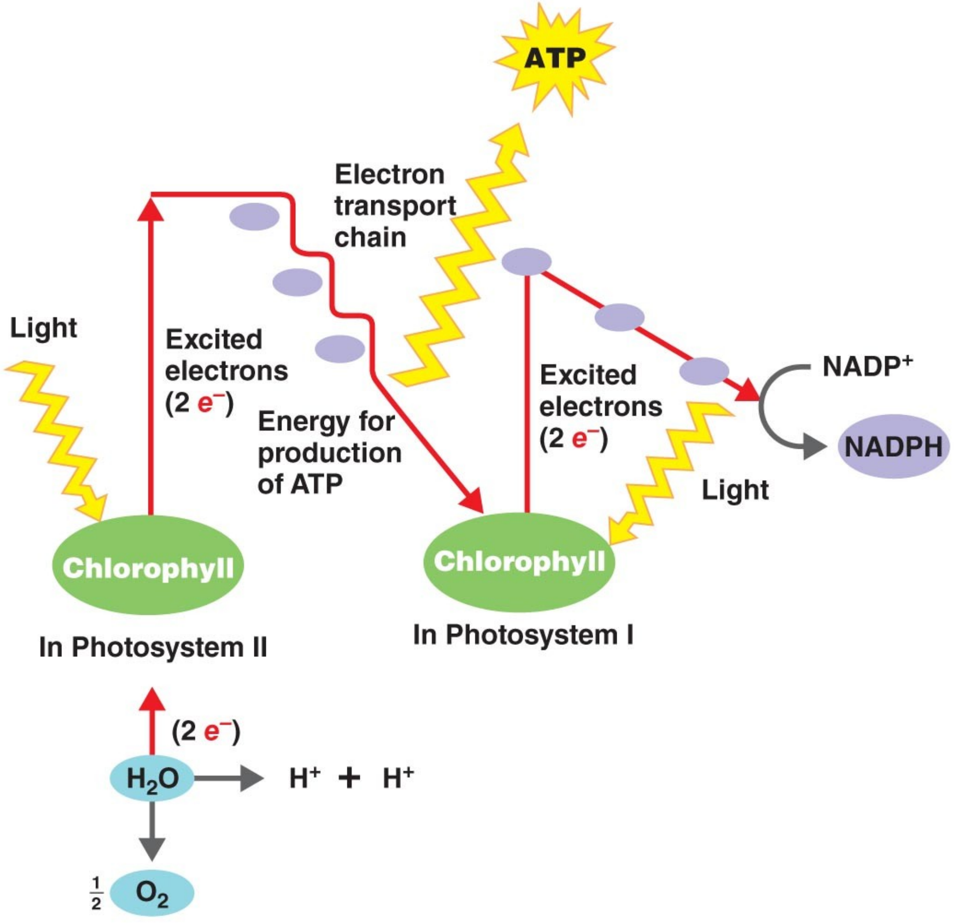


(a) Cyclic photophosphorylation

Photosynthesis: Light Reaction: Noncyclic Photophosphorylation

PLAY **Animation: Photosynthesis: Light Reaction: Noncyclic Photophosphorylation**

Figure 5.25b Photophosphorylation

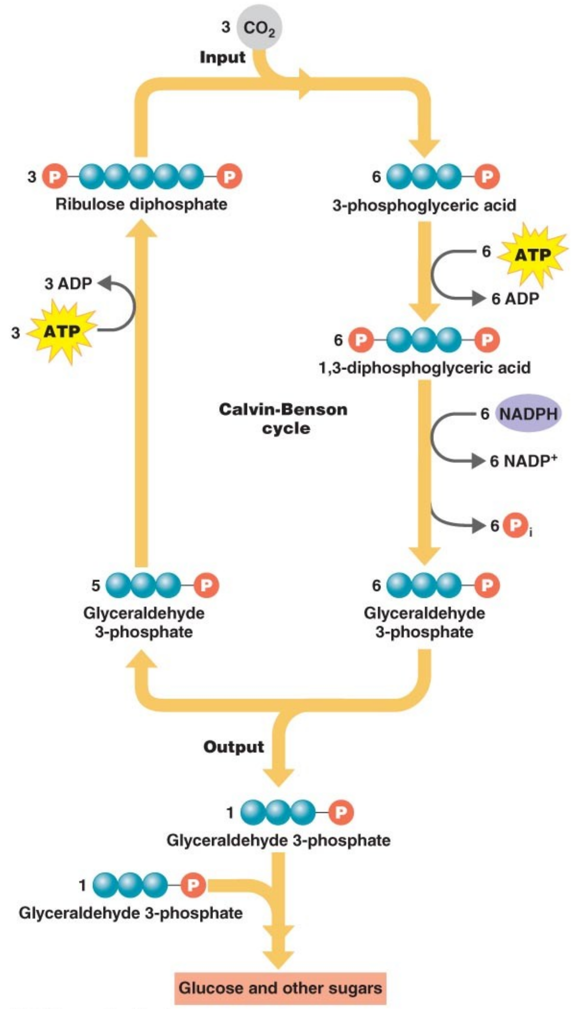


(b) Noncyclic photophosphorylation

Photosynthesis: Light Independent Reaction

PLAY **Animation: Photosynthesis: Light Independent Reaction**

Figure 5.26 A Simplified Version of the Calvin-Benson Cycle



Check Your Understanding-11

Check Your Understanding

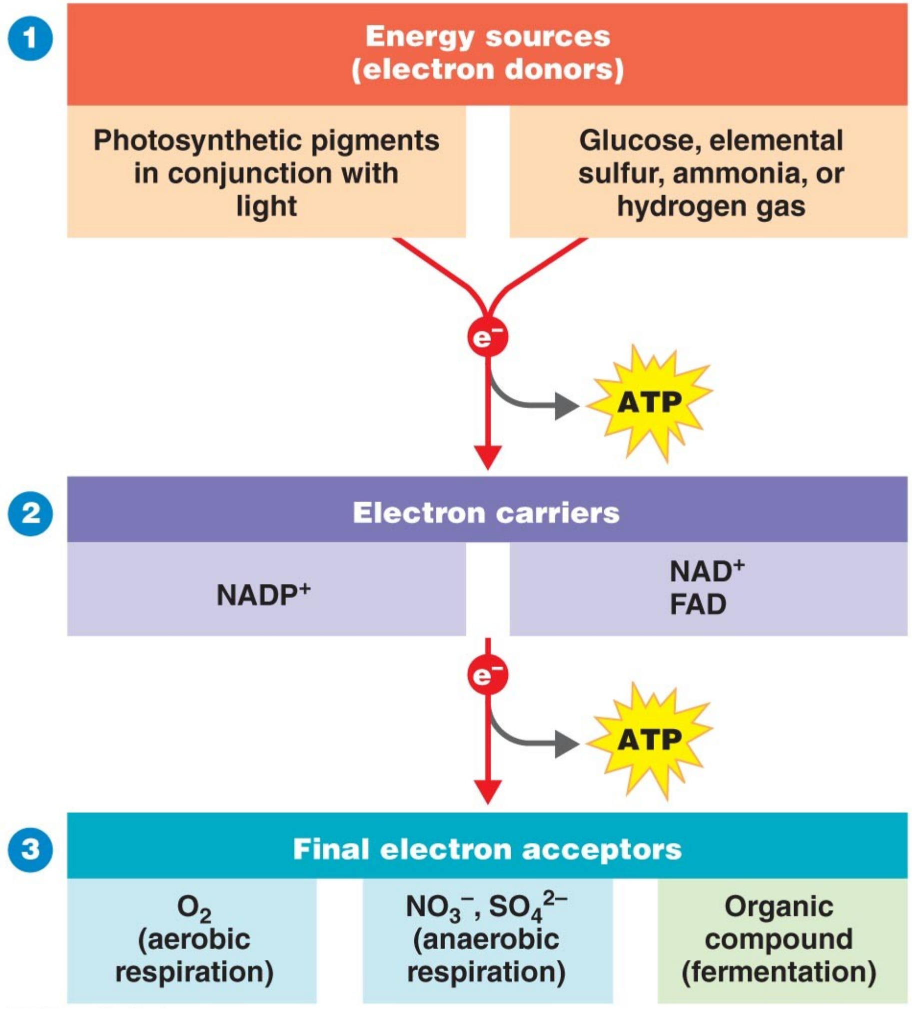
- ✓ How is photosynthesis important to catabolism?
  5-19
- ✓ What is made during the light-dependent reactions?
  5-20
- ✓ How are oxidative phosphorylation and photophosphorylation similar?
  5-21

A Summary of Energy Production

Learning Objective

5-22 Write a sentence to summarize energy production in cells.

Figure 5.27 Requirements of ATP Production



Pearson

Check Your Understanding-12

Check Your Understanding

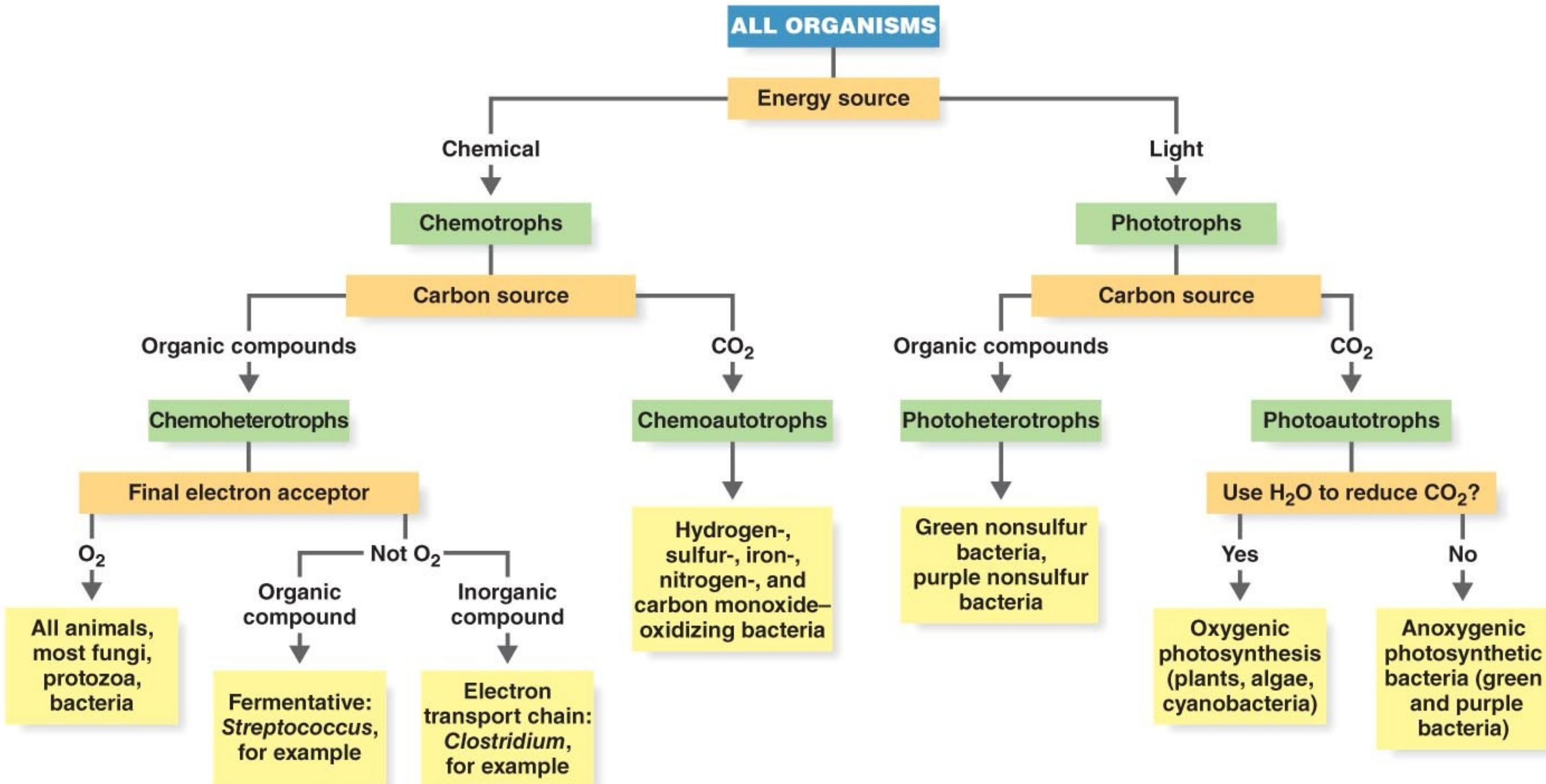
- ✓ Summarize how oxidation enables organisms to get energy from glucose, sulfur, or sunlight.
  5-22

Metabolic Diversity Among Organisms (1 of 4)

Learning Objective

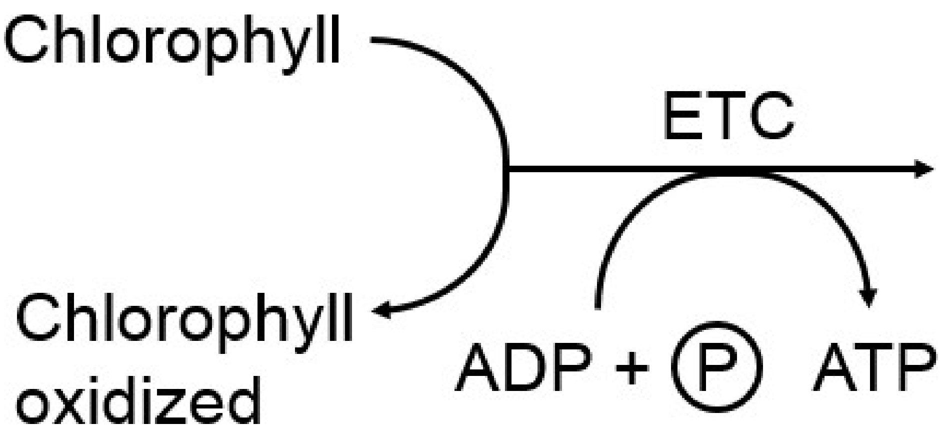
5-23 Categorize the various nutritional patterns among organisms according to carbon source and mechanisms of carbohydrate catabolism and ATP generation.

Figure 5.28 A Nutritional Classification of Organisms



Metabolic Diversity Among Organisms (2 of 4)

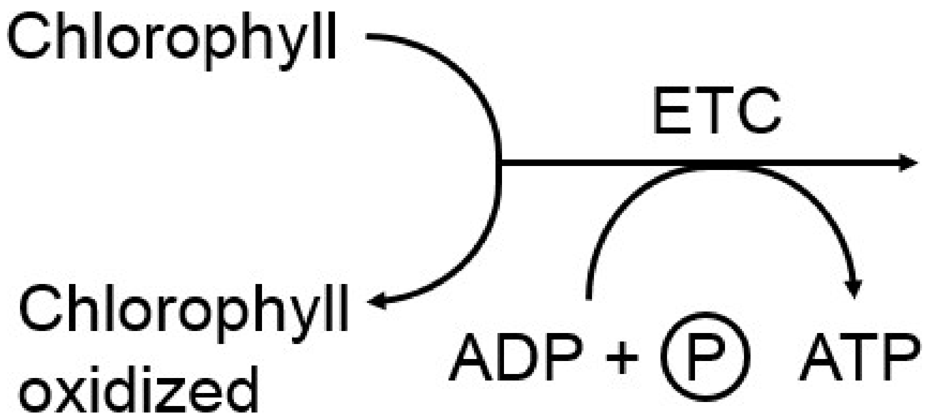
- **Phototrophs** use light energy



- **Photoautotrophs** use energy in the Calvin-Benson cycle to fix CO_2 to sugar
  - **Oxygenic**: produces O_2
  - **Anoxygenic**: does not produce O_2

Metabolic Diversity Among Organisms (3 of 4)

- Phototrophs use light energy



- **Photoheterotrophs** use organic compounds as sources of carbon; anoxygenic

Table 5.6 Photosynthesis Compared in Selected Eukaryotes and Prokaryotes

TABLE 5.6 Photosynthesis Compared in Selected Eukaryotes and Prokaryotes

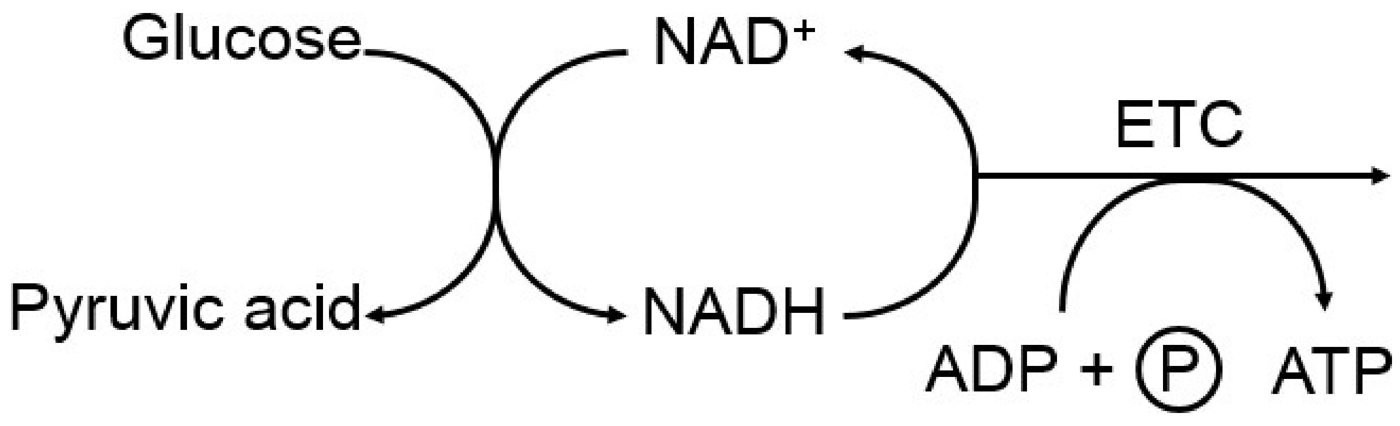
Characteristic	Eukaryotes	Prokaryotes Cyanobacteria	Prokaryotes Green Bacteria	Prokaryotes Purple Bacteria
Substance That Reduces CO_2	H atoms of H_2O	H atoms of H_2O	Sulfur, sulfur compounds, H_2 gas	Sulfur, sulfur compounds, H_2 gas
Oxygen Production	Oxygenic	Oxygenic (and anoxygenic)	Anoxygenic	Anoxygenic
Type of Chlorophyll	Chlorophyll *a*	Chlorophyll *a*	Bacteriochlorophyll *a*	Bacteriochlorophyll *a* or *b*
Site of Photosynthesis	Chloroplasts with thylakoids	Thylakoids	Chlorosomes	Chromatophores
Environment	Aerobic	Aerobic (and anaerobic)	Anaerobic	Anaerobic

Chemoautotrophs (1 of 2)

- Use energy from inorganic chemicals; CO_2 as carbon source
- Energy is used in the Calvin-Benson cycle to fix CO_2

Chemoheterotrophs (2 of 2)

- Use energy and carbon from organic chemicals



- Medically and economically important

Metabolic Diversity Among Organisms (4 of 4)

Nutritional Type	Energy Source	Carbon Source	Example
Photoautotroph	Light	CO_2	Oxygenic: Cyanobacteria, plants Anoxygenic: Green bacteria, purple bacteria
Photoheterotroph	Light	Organic compounds	Green bacteria, purple nonsulfur bacteria
Chemoautotroph	Inorganic Chemical	CO_2	Iron-oxidizing bacteria
Chemoheterotroph	Chemical	Organic compounds	Fermentative bacteria Animals, protozoa, fungi, bacteria

Check Your Understanding-13

Check Your Understanding

- ✓ Almost all medically important microbes belong to which of the four aforementioned groups?
  5-23

Metabolic Pathways of Energy Use

Learning Objective

5-24 Describe the major types of anabolism and their relationship to catabolism.

Figure 5.29 The Biosynthesis of Polysaccharides

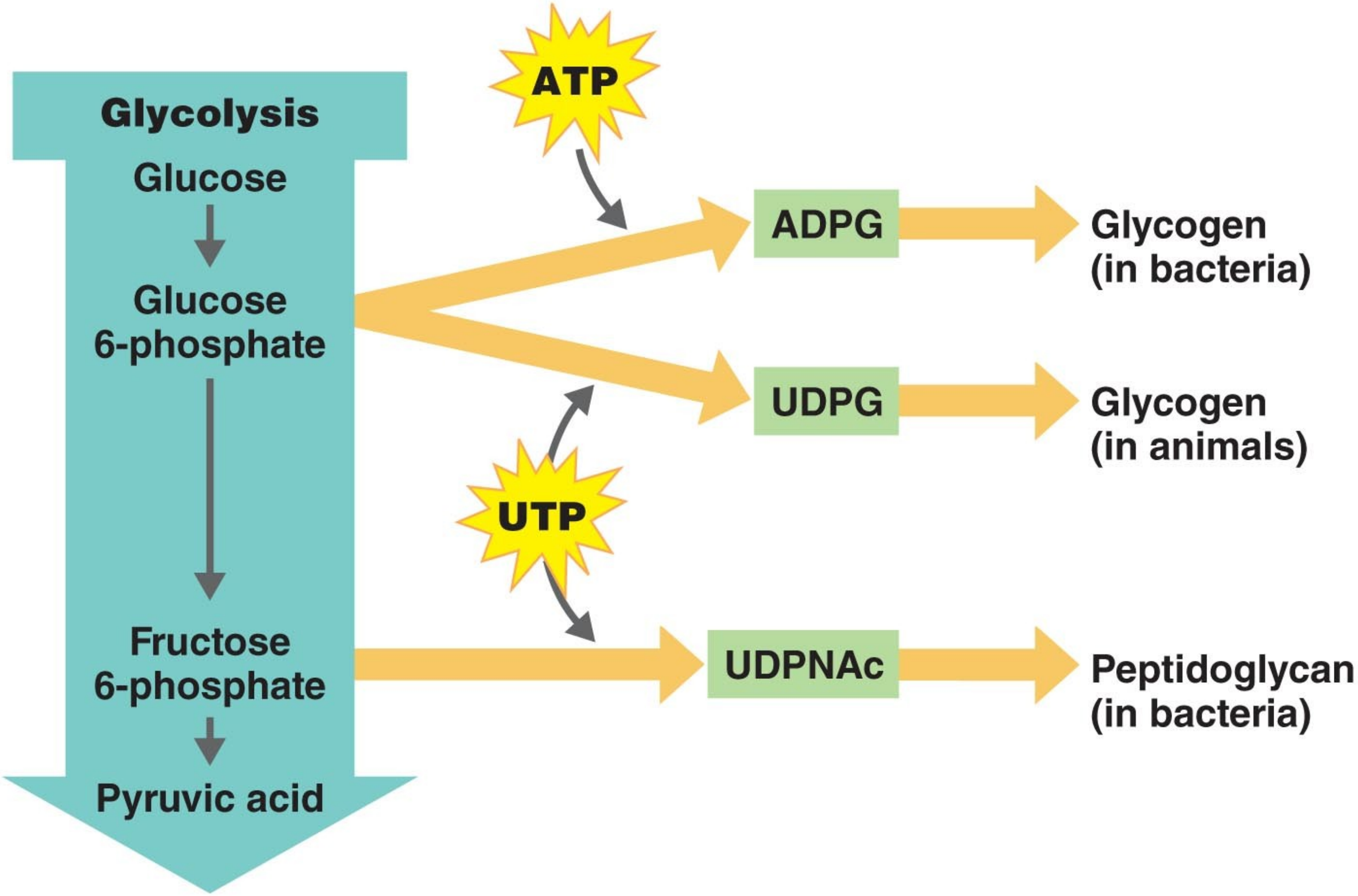


Figure 5.30 The Biosynthesis of Simple Lipids

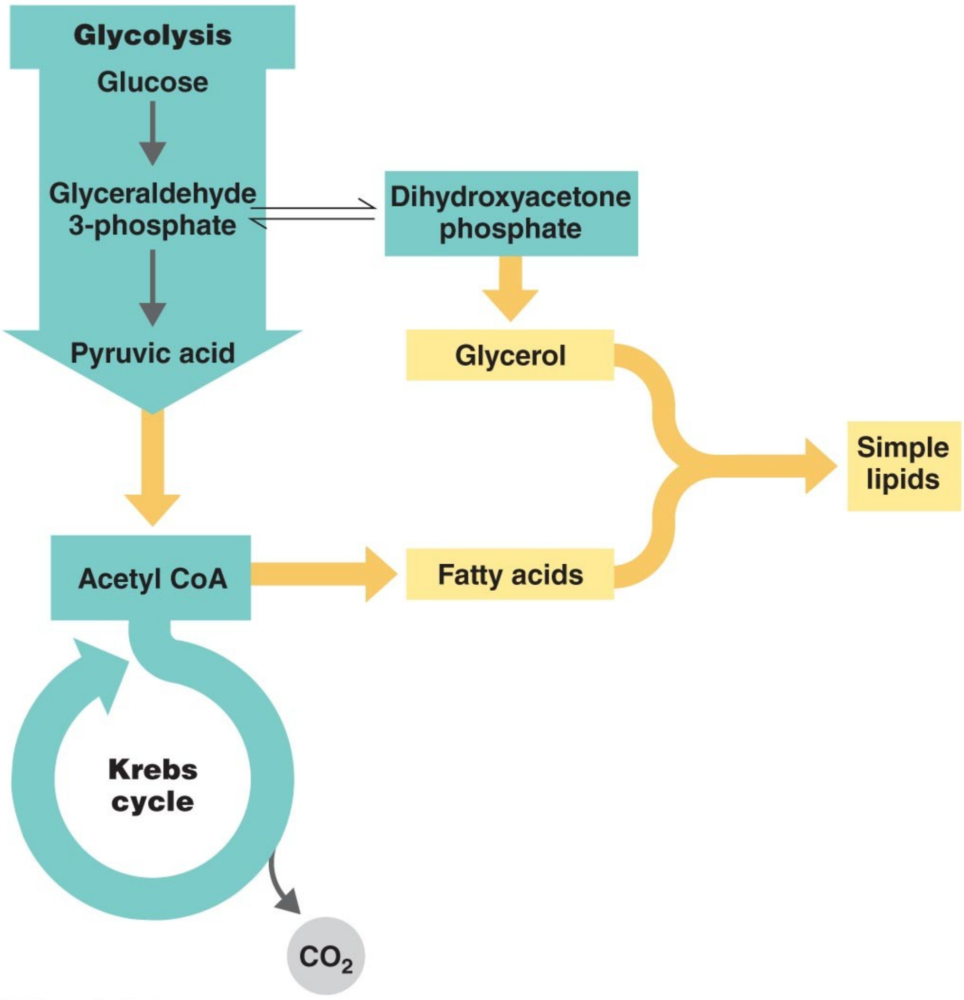
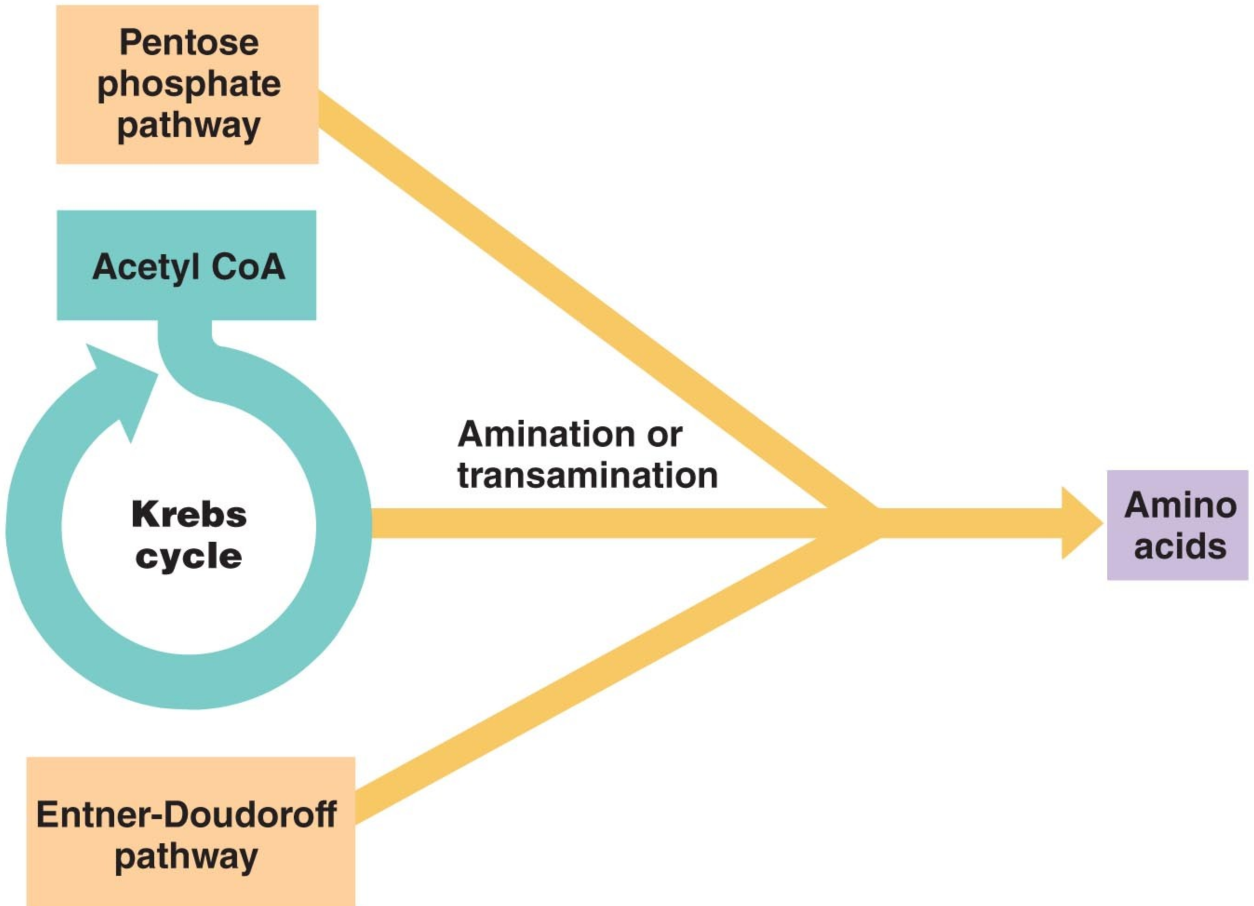
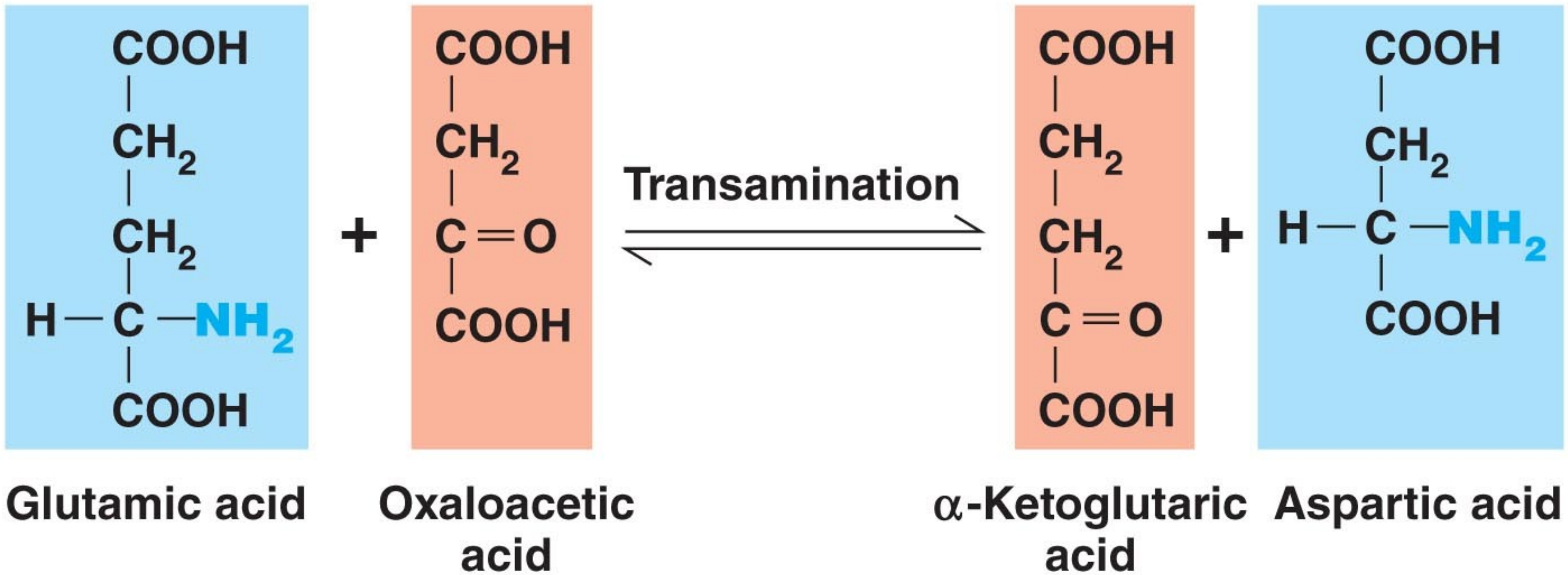


Figure 5.31a The Biosynthesis of Amino Acids



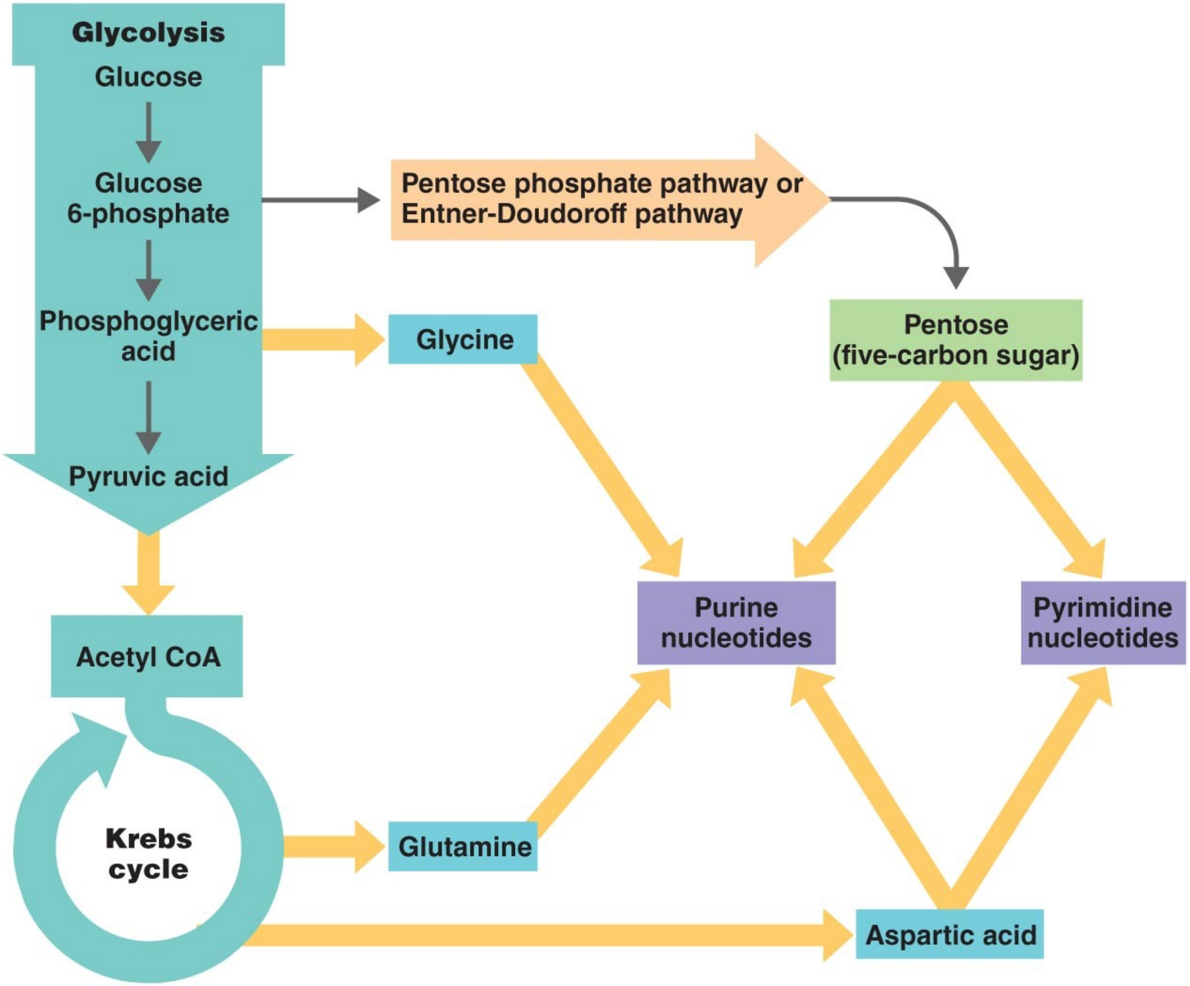
(a) Amino acid biosynthesis

Figure 3.31b The Biosynthesis of Amino Acids



(b) Process of transamination

Figure 5.32 The Biosynthesis of Purine and Pyrimidine Nucleotides



Check Your Understanding-14

Check Your Understanding

- Where do amino acids required for protein synthesis come from?
  5-24

The Integration of Metabolism
(1 of 2)

Learning Objective

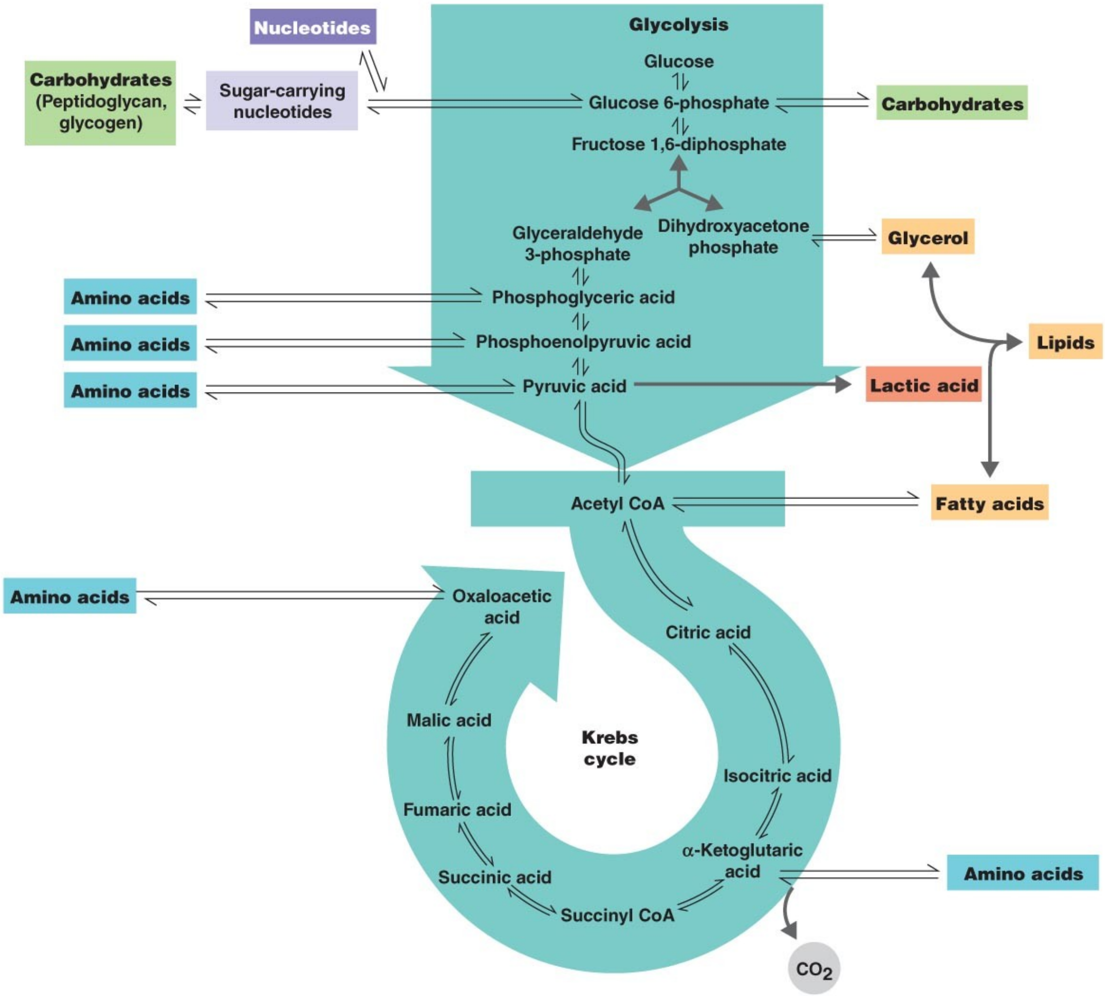
5-25 Define **amphibolic pathways**.

The Integration of Metabolism

(2 of 2)

- **Amphibolic pathways:** metabolic pathways that function in both anabolism and catabolism
- Many pathways function simultaneously with common intermediates

Figure 5.33 The Integration of Metabolism



Pearson

Metabolism: The Big Picture

PLAY **Animation: Metabolism: The Big Picture**

Check Your Understanding-15

Check Your Understanding

- ✓ Summarize the integration of metabolic pathways using peptidoglycan synthesis as an example.
  5-25